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GDC-ASP79-001

LUNAR RESOURCES UTILIZATION FOR SPACE CONSTRUCTION

FINAL REPORT

VOLUME I • EXECUTIVE SUMMARY

CONTRACT NO. NAS9-15560
DRL NO. T-1451
DRD NO. MA-677T
LINE ITEM NO. 4

30 April 1979

Submitted to
National Aeronautics and Space Administration
LYNDON B. JOHNSON SPACE CENTER
Houston, Texas 77058

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(NASA-CR-173023) LUNAR RESOURCES UTILIZATION FOR SPACE CONSTRUCTION. VOLUME 1: EXECUTIVE SUMMARY Final Report, Apr. 1978 - Feb. 1979 (General Dynamics/Convair) 65 p

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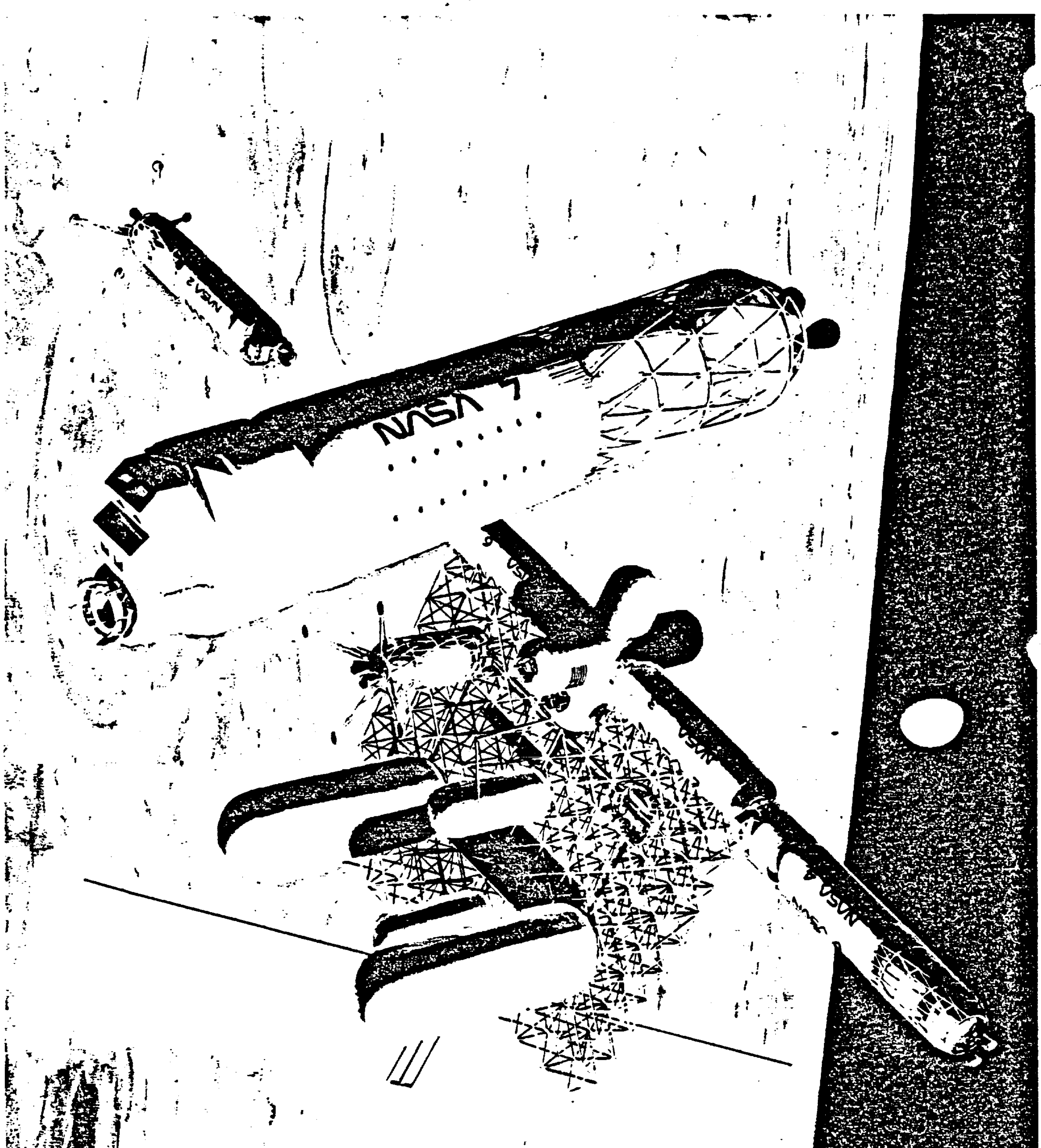

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FOREWORD

This final report was prepared by General Dynamics Convair Division for NASA/JSC in accordance with Contract NAS9-15560, DRL No. T-1451, DRD No. MA-677T, Line Item No. 4. It consists of three volumes: (I) A brief Executive Summary; (II) a comprehensive discussion of Study Results; and (III) a compilation of Appendicies to further document and support the Study Results.

The study results were developed from April 1978 through February 1979, followed by preparation of the final documentation. Reviews were presented at JSC on 18 October 1978 and 21 February 1979.

Participants who significantly contributed to this study include General Dynamics Convair personnel, a materials processing and manufacturing consultant, and five technical reviewers who are nationally recognized authorities on lunar materials and/or space manufacturing.

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In addition to these participants, useful supportive information was obtained from two complementary study activities, from personnel at NASA's Johnson Space Center and Lewis Research Center, and from many academic and industrial researchers who are involved with development of manufacturing processes which may be especially suited for in space use.

- Contract NAS09-051-001 "Extraterrestrial Materials Processing and Construction" being performed by Dr. Criswell of LPI under the direction of JSC's Dr. Williams.

- Contract NAS8-32925 "Extraterrestrial Processing and Manufacturing of Large Space Systems" being performed by Mr. Smith of MIT under the direction of MSFC's Mr. von Tiesenhausen.

- Earth Baseline Solar Power Satellite costing information from Mr. Harron, Mr. Whittington, and Mr. Wadle of NASA's Johnson Space Center.

- Ion Electric Thruster information for argon and oxygen propellants provided by Mr. Regetz and Mr. Byers of NASA's Lewis Research Center.

- Electron Beam Vapor Deposition of Metals Information from Dr. Schiller of Forschungsinstitut Manfred Von Ardenne, Dresden, and Dr. Bunshah of UCLA, plus others.

- Solar Cell Manufacturing Information from Mr. Wald of Mobile Tyco Solar Energy Corp., Mr. Minnucci and Mr. Younger of SPIRE Corp., and Mr. Dubik of Schott Optical Glass Co., plus others.

- Glass Manufacture Using Lunar Materials Information from Dr. MacKenzie of UCLA.

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LIST OF ACRONYMS

ACS	Attitude Control System
COR	Contracting Officers Representative
COTV	Cargo Orbital Transfer Vehicle
CRES	Corrosion Resistant Steel
CTV	Cargo Transfer Vehicle
DOE	Department of Energy
DRD	Data Requirement Description
DRL	Data Requirements List
ECLSS	Environmental Control & Life Support System
EMR	Earth Material Requirements
ET	External Tank (Space Shuttle)
EVA	Extra Vehicular Activity
GDC	General Dynamics Convair
GEO	Geostationary (or Geosynchronous) Earth Orbit
HLLV	Heavy Lift Launch Vehicle
ISP	Specific Impulse
JSC	Johnson Space Center (NASA)
L_2	Lagrangian Libration Point Behind Moon
L_4 or L_5	Lagrangian Libration Point which Forms an Equalateral Triangle with Earth and Moon
LDR	Lunar Derived Rocket
LEO	Low Earth Orbit
LeRC	Lewis Research Center (NASA)
LLO	Low Lunar Orbit
LMR	Lunar Material Requirements
LPI	Lunar and Planetary Institute
LRU	Lunar Resource Utilization
LS	Life Support
LSS	Large Space Structure
LTV	Lunar Transfer Vehicle
MBE	Molecular Beam Epitaxy
MDRE	Mass Driver Reaction Engine
MIT	Massachusetts Institute of Technology
MPTS	Microwave Power Transmission System
MSFC	Marshall Spaceflight Center (NASA)
NASA	National Aeronautics and Space Administration
OTV	Orbital Transfer Vehicle
PLTV	Personnel Lunar Transfer Vehicle
PLV	Personnal Launch Vehicle

LIST OF ACRONYMS (cont'd)

POTV	Personnel Orbital Transfer Vehicle
RDT&E	Research, Development, Test and Evaluation
RMS	Remote Manipulator System (Space Shuttle)
RPL	Rotary Pellet Launcher
SCB	Space Construction Base
SDV	Shuttle Derived Vehicle
SEP	Solar Electric Propulsion
SMF	Space Manufacturing Facility
SPS	Solar Power Satellite or Satellite Power Station
SRB	Solid Rocket Booster (Space Shuttle)
SSME	Space Shuttle Main Engine
SSTS	Space Shuttle Transportation System
TFU	Theoretical First Unit
TT	Terminal Tug
UCLA	University of California at Los Angeles
WBS	Work Breakdown Structure

ENGLISH CONVERSIONS

1 kilogram (kg) = 2.205 lb

1 meter (m) = 39.372 inches = 3.281 ft

1 ton = 1000 kg = 2205 lb

1 square meter = 10.76 square feet

1 micrometer (μm) = 10^{-6} meters = 10^{-3} millimeters (mm) = 3.94×10^{-5} inches

°C = (°F-32) 5/9 = °K-273°

1 kilometer (km) = 0.6214 mile

1 square kilometer = 0.3861 square mile

1 gravitational constant (g) = 9.806 m/sec^2 = 32.2 ft/sec^2

1 Newton = 0.2248 lb$_F$

Specific Impulse (I_{sp}) $= \dfrac{\text{Newton-second}}{\text{kg}}\left(\dfrac{\text{N}\cdot\text{s}}{\text{kg}}\right)$

= 9.806 (ISP in seconds)

Pressure = N/cm^2 = 0.689 lb$_F$/in^2

1 Pa = 1N/m^2

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INTRODUCTION

1.1 LUNAR RESOURCES UTILIZATION CONCEPT

The lunar resources utilization (LRU) concept involves use of lunar materials rather than materials obtained from earth for in-space construction projects. In this concept, lunar surface material would be mined, processed to obtain useful elements such as silicon, oxygen, aluminum and iron, and fabricated into satellites capable of providing useful earth services and generating revenues. Lunar resource utilization involves an expanded manned space program regarding activity locations and total in space personnel as compared to an equivalent earth based satellite construction program.

Potential benefits associated with LRU:

- Lower energy requirements for delivery of material from moon to geosynchronous earth orbit (GEO) than from earth to GEO, results in reduced transportation costs.
- Significantly reduced earth material requirements since the majority of construction materials are obtained from the moon. Reduced depletion of earth resources.
- Significantly reduced earth launch vehicle requirements due to lower payload requirements. This results in reduced propellant consumption and atmospheric pollution. Launch vehicle size and flight schedule can also be reduced.
- Economic and social gains acruing from these reduced earth activities, assuming that equivalent revenue generating satellites can be produced with lunar resources.

1.2 STUDY SCOPE

The study developed and compared equivalent LRU and reference earth baseline space construction scenarios to determine the project size needed for LRU to be economically competitive. This project size was identified as the material requirements threshold at which lunar resources utilization may become cost effective. Alternative LRU techniques were evaluated to determine threshold sensitivity to material processing location and lunar material transfer methods.

Assessment included conceptual definition of LRU major system elements, development of element costs, and total program costs. This information was obtained as much as possible from available literature and results of previous and current NASA-industry studies. The study goal was to perform an equitable comparison of LRU concepts with the earth baseline, using compatible ground rules and cost estimating procedures.

1.3 OBJECTIVES AND APPROACH

Overall objectives of the lunar resources utilization study were:

- Establish evaluation criteria to compare manufacture of space structures with lunar or earth materials
- Define lunar resource utilization concepts and conduct an initial feasibility assessment
- Establish the material requirements threshold where lunar resource utilization becomes cost effective
- Determine conditions under which a series of decisions to pursue use of lunar materials would be justified
- Prepare plans and recommendations for further work needed to permit a future choice between space manufacturing scenarios.

These five objectives were addressed by seven study tasks:

	Executive Summary Subsection
• Comparison methodology and criteria	2.1
• Material requirements range and scenario development	2.2
• Lunar utilization systems concepts definition	2.3
• Preliminary LRU cost effectiveness determination	2.4
• Preliminary decision analysis	2.5
• Sensitivity and uncertainty analyses	2.4
• Recommendations	2.5

Results presented in the following section have been organized to correspond to accomplishments within each of these tasks. Each task is allocated its own subsection except that all cost related information is contained in 2.4, and programmatic related results are combined in 2.5.

SI (metric) units have been used for principal calculations and all reporting of LRU study results unless specifically noted otherwise. Metric tons (1,000 kg) are indicated with the symbol T. Prefixes k, M and G deonte values of 10^3, 10^6, and 10^9, respectively. Thus, MT refers to millions of metric tons.

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STUDY RESULTS

Study task activity results are summarized in the following subsections. Supportive information associated with these results is contained in Volumes II and III of this final report.

2.1 COMPARISON METHODOLOGY

Development of comparison methodology and evaluation criteria included preparation of study guidelines, identification of evaluation criteria, and development of a comparison methodology for LRU concept assessment.

GUIDELINES

- UTILIZE THE SOLAR POWER SATELLITE (SPS) PROGRAM DEFINED BY JSC's JANUARY 25, 1978 SYSTEM DEFINITION DOCUMENT AS THE REFERENCE EARTH BASELINE — This program defines steady state production of one 10 GW SPS per year for 30 years with cost estimates based on 1977 dollars. Subsequent study results confirmed that an ambitious space construction program such as SPS was probably needed to justify LRU consideration.

- LUNAR RESOURCE UTILIZATION GUIDELINES SHALL BE COMPATIBLE WITH THOSE FOR EARTH BASELINE — Since steady state SPS production was used for the earth baseline, LRU satellite construction was also constrained to steady state for comparative assessment. An alternative technique, bootstrapping, results in a continually increasing production rate, which is incompatible with the earth baseline, and makes comparison difficult.

- USE PROJECTED 1990 TECHNOLOGY FOR DEFINITION OF SPACE MANUFACTURING FACILITIES — All lunar mining, material processing, and fabrication facilities plus their handling and logistics equipment shall be automated to projected 1990 technology levels. This guideline shall be applied for estimating facility mass, facility power, and personnel requirements.

EVALUATION CRITERIA

- TOTAL PROGRAM COST SHALL BE THE BASIC CRITERION FOR ASSESSING LUNAR RESOURCES UTILIZATION — Other secondary assessment criteria include earth material requirements and environmental considerations.

COMPARISON METHODOLOGY

The approach toward meeting study objectives included development of an itemized procedure for comparison of lunar resources utilization concepts with a reference earth baseline satellite construction technique:

- ESTABLISH SATELLITE PRODUCTION REQUIREMENTS — Development of a representative manufacturing scenario and its associated material requirements was accomplished to permit LRU assessment.

- DEFINE CANDIDATE CONCEPTS — Alternative lunar resources utilization concepts were differentiated by in-space activity locations and the transport techniques employed for transfer of raw materials, cargo, and personnel. Generalized LRU systems concepts representative of space based, lunar based, and combination space/lunar based operating scenarios were initially postulated.

- DEVELOP STEADY STATE MATERIAL LOGISTIC SCENARIOS — Steady state material logistics scenarios were developed for each of these alternative concepts to determine the quantity of earth and lunar materials required to support a space construction program. LRU element sensitivity was developed by assessing the effect of various options on earth material requirements. The earth material requirement (EMR) is defined as the kilograms of material that must be launched from earth (including propellants) for each kilogram of completed large space structure in geosynchronous orbit. This figure of merit was applied for steady-state comparisons. EMR was an extremely useful figure of merit since it reflected the overall steady state operational efficiency of lunar resource utilization options, as compared to the earth baseline, and permitted elimination of non-competitive concepts prior to costing. This was substantiated by study results.

- ITERATE TO OBTAIN IMPROVED CONCEPTS WITH LOW EARTH MATERIAL REQUIREMENTS — Three representative LRU concepts were obtained by iterative process which used minimum EMR as the selection criteria. These three LRU implementation techniques are identified in Table 2-1 as Concepts B, C and D, along with the reference earth baseline, Concept A. They are characterized by the material processing location and the launch vehicle employed for transporting material from the moon. Concept development resulted in the use of similar transportation elements for transfer of cargo and personnel between activity locations other than lunar surface to low lunar orbit.

- DETERMINE VEHICLE & FACILITY SIZING REQUIREMENTS — Logistics scenarios, which define earth and lunar material needs including vehicle

Table 2-1. Alternative construction concepts.

Designation	Earth launch vehicle	Material processing location	Lunar material launch vehicle		
			Description	Propellant	Propellant source
Reference earth baseline A	HLLV	Earth	—	—	—
LRU concept B	SDV	In-space	Mass driver catapult & mass catcher	Electricity Oxygen	Solar or nuclear Moon
LRU concept C	SDV	Lunar surface	Chemical rocket	Oxygen & hydrogen	Moon Earth
LRU concept D	SDV	Lunar surface	Chemical rocket	Oxygen & aluminum	Moon Moon

propellants at each activity location, were employed in conjunction with the required satellite production rate to determine vehicle and facility sizing requirements data.

- GENERATE ELEMENT COST DATA — System element costs were then developed based on this steady state sizing information. Some elements were similar or identical for more than one LRU system concept, therefore, so were their costs. Element costs included development, production, and operating costs.

- DEVELOP START-UP INFORMATION & COST — The steady state sizing information was also used to define start-up requirements and associated costs.

- OBTAIN TOTAL LRU CONCEPT PROGRAM COSTS — System element costs for each LRU concept were then combined with start-up costs to develop total program costs for each nominal LRU concept over a fixed 30 year operational period.

- COMPARE WITH EARTH BASELINE PROGRAM COST TO DETERMINE MATERIAL REQUIREMENTS THRESHOLD — LRU program costs were then compared with earth baseline costs developed using compatible groundrules, to define a preliminary material requirements economic threshold. This threshold determined the material utilization level in geosynchronous orbit at which LRU became competitive with earth resource utilization.

- GENERATE COST SENSITIVITY AND UNCERTAINTY DATA — This initial nominal threshold was then revised to account for the effects of cost and technical uncertainties.

- PERFORM PRESENT VALUE ECONOMIC COMPARISON OF LRU CONCEPTS & THE EARTH BASELINE — Total nominal program costs were revised to account for cost discounting (a present value economic analysis) and compared.

2.2 MATERIAL REQUIREMENTS AND SCENARIO DEVELOPMENT

The purpose of this task was to establish a range of credible material requirements for which the potential of lunar resources utilization could be assessed. Determination of satellite material requirements was conducted in four steps:

- An investigation of three mission scenarios and associated satellite material requirements was performed to determine if other than SPS requirements had any significant influence. These three scenarios were:

    1) A low scenario without solar power satellite (SPS)
    2) An intermediate scenario combining SPS's and the low scenario
    3) A high scenario consisting exclusively of SPS's

- Established the specific earth material used for each major satellite component or application, and the performance requirements which resulted in the selection of this material.

- Postulated suitable component substitutes which contain a reasonably high percentage of lunar materials and satisfy most (or all) of the baseline component's performance requirements. Determined the equivalent quantity of this substitute lunar material needed to meet earth baseline performance requirements. Selected those components for which this substitution could be reasonably made. This material replacement occurred in successively more difficult steps, from direct replacement to substitutions requiring satellite redesign.

- Determined the corresponding lunar and earth material requirements for satellite systems constructed primarily with lunar resources.

2.2.1 SCENARIO DEVELOPMENT. The major issue requiring resolution in development of mission scenarios was whether satellites other than SPS contribute unique material requirements or sufficient mass requirements to influence LRU program definition.

There were two realistic assumptions which were made concerning candidate satellites used for initial justification of lunar resource utilization:

1) They should either be multiple identical satellite systems or consist of a family of similar satellites. This is valid since construction of unique satellites cannot be used to justify an in-space mass production facility. This is true for satellite construction using either earth or lunar-derived materials.

2) The satellites should be located in a high earth orbit such as geosynchronous. This is important since the lunar resource utilization concept's economic effectiveness is primarily based on reduced transportation costs. The ΔV required to bring lunar material to LEO is approximately equivalent to that for orbiting material from earth's surface. For comparison, the ΔV for lunar material utilization at GEO is 28% of that for earth material.

A low scenario was developed with satellites obtained from the Aerospace Corporation report (Reference 1) which satisfied assumptions 1) and 2). The forty-two civilian initiatives identified in this report to provide future observation, communications, and support services resulted in 25 acceptable candidate service satellites, and did not include the Solar Power Satellite (SPS), which was purposely omitted from this scenario. The global network consisted of 470 satellites constructed during a thirty year period, with a total mass of 63,230T.

The second step was to determine if this low scenario could be within the material requirements threshold range needed to justify lunar resources utilization. To evaluate this, cost data developed during the 1975 NASA Ames Summer Study on Space Settlements (Reference 2) for construction of SPS using lunar materials was compared with NASA-JSC's preliminary earth baseline concept (Reference 3). Although many inconsistencies exist in the guidelines and methodology used for these two estimates, their comparison resulted in a "preliminary nominal threshold point" of 5.8 10 GW SPS, or approximately 565,000 tons of material. This means that the low scenario which does not include SPS must be increased by a factor of 9, or combined with material requirements for other satellites such as SPS, to meet this "preliminary nominal threshold point" criteria.

The third step evaluated whether combined SPS and other satellite material requirements are significantly different than SPS material requirements alone. To accomplish this, an overall comparison of two possible intermediate scenarios at the "preliminary nominal threshold point" was conducted. One scenario consisted entirely of solar power satellites. The other scenario consisted of a combination of SPS's and compatible earth service satellites. The total mass of both options was the same, and equaled the material requirements threshold point equivalent to 5.8 SPS's. Comparison of material quantities identified a maximum variation of two percent. For high material scenarios, the percent variations would become significantly smaller. Based on this analysis, it is evident that if SPS material requirements are exclusively used over the entire mission scenario range, the nominal error for any specific material requirement will be only two percent. Historical experience indicates that cost uncertainties will actually result in greater thresholds than this preliminary nominal, and the resulting material requirements error will be correspondingly lower. This nominal error is well within our current ability to predict actual SPS material requirements, and is therefore insignificant. Thus, we recommended that SPS material requirements as a function of SPS construction rate be used exclusively throughout the mission scenario range. SPS has been used for LRU evaluation due to its conceptual definition status, its substantial mass, and the potential requirement for producing a significant quantity. Any alternate equivalently massive product should be equally applicable for LRU assessment.

2.2.2 EARTH CONSTRUCTION MATERIALS. The solar power satellite configuration employed for material requirements definition is the design described in NASA-JSC's recommended preliminary baseline concept (Reference 3), which was primarily derived from the Boeing SPS System Definition Study, Part II (Reference 4).

This satellite power system delivers total ground power of 10 GW via two rectennas of 5 GW each. The satellite, depicted in Figure 2-1, has a central solar array with a microwave transmitting antenna mounted at each end. These antennas are steerable so they can continuously transmit to two separate ground receivers while the photovoltaic array remains sun oriented. The array consists of glass covered silicon solar cells with a concentration ratio of 1, mounted on a graphite composite structure. Flat aluminum sheets are used to collect the electrical power and conduct it to the antennas. Three concentric coin silver coated graphite composite slip rings with silver brushes are used for power transmission across each antenna rotary joint. Antennas are constructed with graphite composite structure which supports aluminum coated graphite

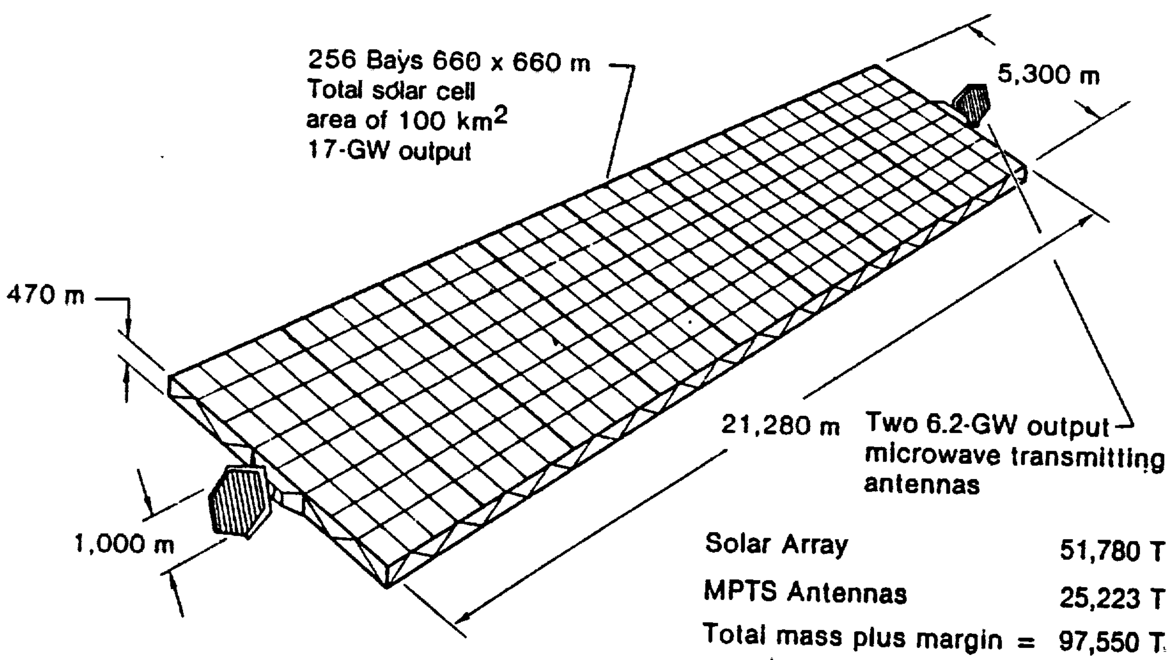


Figure 2-1. Reference baseline solar power satellite.

composite waveguides. To each antenna are mounted 228 DC/DC converters and 97,056 klystrons plus their radiators, which convert the solar array DC power to microwave energy.

Development of lunar resource requirements for the satellite power system required an understanding of the earth baseline material performance characteristics. To obtain this understanding of specific SPS material applications, a materials matrix was generated using satellite mass summary data and material requirements summary data obtained from Reference 3, plus information from volumes III, IV and VI of Reference 4. Identical materials of similar configuration (i.e., sheet, wire, etc.) and similar performance requirements were collected along with their share of the margin to obtain a comprehensive composite listing. This resulted in fifteen discrete material products, ranked by their mass, each contributing at least 1.2 percent of total SPS mass, which totaled 90.0 percent of the earth baseline SPS material requirements. The remaining 10 percent, or 9,750 T, consisted of small quantities of various assorted materials such as silver, tungsten, and mercury, along with electronic components and other complex devices, which must be obtained from earth.

2.2.3 LUNAR MATERIAL SUBSTITUTIONS. Each of the fifteen earth material applications were investigated to determine reasonable alternative methods of providing the same function with lunar derived materials. This investigation included development of equivalent material requirements. The recommended lunar material substitutions are summarized in Table 2-2 for these fifteen SPS applications. Substitute material replacement mass factors vary from 0.34 for replacing the CRES klystron housing with aluminum, to 3.67 for replacing graphite composite structure with foamed glass. Postulation of a low density lunar ceramic (foamed glass) as suitable SPS structure was based on the theoretical attributes of this material, especially its low coefficient of thermal expansion. Extensive technology development will be required to obtain such a material.

By combining all four of Table 2-2's categories, 90 percent of the original earth baseline SPS material requirements were satisfied with lunar materials. It is important to note, however, that the total SPS mass increased when lunar glass structure was substituted for earth graphite composite. Since all of these substitutions should be feasible if reasonable technology developments are pursued, we have recommended that all fifteen candidate SPS applications be implemented with the designated lunar resource substitutions.

2.2.4 LRU SPS MATERIAL REQUIREMENTS. Table 2-3 summarizes the lunar and earth material requirements for a lunar resource 10GW SPS, assuming successful material substitution in all four categories. Both original and updated results are shown.

Table 2-2. Recommended lunar material substitutions.

Category		Percent
Direct replacement of earth materials	• Aluminum for power busses & radiators • Silicon for solar cells • Fused silica glass for solar cell substrate • Iron for Klystron poles & transformer core	38.1
Simple substitution for earth materials	• Fused silica for borosilicate glass solar cell covers • Aluminum for copper wire & interconnects • Aluminum for copper radiators	31.4
Difficult substitution for earth materials	• Alloy steel for CRES heat pipes • Copper coated aluminum for copper Klystron cavity • Aluminum for CRES Klystron cavity	7.5
Substitution requires minor SPS redesign	• Foamed glass for graphite composite structure • Foamed glass for graphite composite waveguides	13.0

The updated SPS material requirements include estimates of the nonrecoverable losses of both lunar and earth supplied materials occurring in the various stages of converting metallic and nonmetallic elements into stock materials, parts, components and subassemblies. The nonrecoverable losses of lunar materials at all stages of production are low; in the range of 0.1 to 0.2% since any scrap material can readily be recovered by reprocessing. However, the nonrecoverable losses of many lunar and earth supplied alloying elements may be much higher, in the order of 5-10%, since it will not generally be worth the effort and expenditure of energy to recover them from scrapped foamed glass, metallic alloys, etc.

Comparison of the original and updated material requirements data in Table 2-3 shows an increase of 19.8 percent in lunar material requirements, and an increase of 22.6 percent in earth material requirements. Although unrecoverable materials were responsible for some of this increase, revised foamed glass requirements and other material quantity changes in the completed LRU solar power satellite were major contributors. The updated SPS mass for construction with lunar materials is 112,220 T, with 101,920 T manufactured from lunar material and 10,300 T obtained from earth. This represents an increase of 15 percent in completed satellite mass from the 97,550 T reference earth baseline.

Table 2-3. Summary of LRU SPS material origin.

	Earth material		Lunar material		Completed SPS	
	Mass (T)	%	Mass (T)	%	Mass (T)	% increase
Reference earth baseline	97,550	100	—	—	97,550	—
Original LRU for concept evaluation	10,190	10.4	88,190	89.6	98,380	0.9
Updated LRU with processing losses	12,490	10.6	105,650	89.4	112,220	15.0

2.3 LRU SYSTEMS CONCEPT DEFINITION

Definition of alternative lunar resources utilization system concepts was accomplished for comparison with the reference earth baseline SPS construction scenario. Their definition and assessment was conducted in five steps:

- Definition of representative techniques for utilizing lunar resources to construct solar power satellites. Three basic concepts were developed from these techniques which represent a broad spectrum of alternatives. These concepts have previously been identified in Table 2-1.

- Development of steady state material logistics scenarios for each concept. This provided sizing data for the major system elements needed to process and transport SPS construction materials, propellants, and personnel.

- Definition of major system elements. The processing and manufacturing, transportation, and infrastructure support elements of each LRU concept were defined. Material processing covers those activities from mining of raw materials through final assembly of usable end items. Transportation is a major element since the material processing activities occur at various locations in the earth-space-moon environment. Both personnel and material must be transported between activity sites. Infrastructure support elements encompass all other activities necessary to accomplish the material processing and transportation activities, such as habitats, propellant depots, and power generating facilities.

- Description of the lunar material flow and composition from surface mining through its combination with earth components to construct a solar power satellite.

- Generation of start-up scenarios for delivering all space facilities, vehicles, initial supplies, initial propellants, and personnel to proper locations and placing them on operational status to support steady state production.

2.3.1 CONCEPT DEFINITIONS. The reference earth baseline and lunar resources utilization concepts are defined schematically in Figure 2-2 by activity locations and transport vehicle descriptions.

The earth baseline material utilization scenario, as defined in Reference 3, is based on techniques developed and perfected during NASA's past space accomplishments but implemented on a much larger scale. Two earth-to-LEO launch vehicles are employed: a fully reusable heavy lift launch vehicle (HLLV) for cargo, and a shuttle derived personnel launch vehicle (PLV). The HLLV is a 2-stage fly-back vehicle with chemical propulsion and 424-ton payload capability. Its payload consists of crew support stations, fabrication machinery, assembly jigs, orbital transfer vehicles (OTV), and all construction supplies and OTV propellants. The PLV replaces the Shuttle's tandem burn solid rocket boosters with a series-burn O_2/methane ballistic entry first stage, and has an Orbiter modified to carry 75 passengers with their personal equipment.

Eight large structural SPS sections are fabricated, inspected and checked out in LEO. These completed sections are transferred to their operational location with expendable unmanned cargo orbital transfer vehicles (COTV) powered by partially deployed photovoltaic arrays on the SPS segments. The COTV uses a low-thrust/high-impulse ion-electric propulsion system and argon propellant. Final assembly of these satellite sections into the complete solar power satellite is performed at its GEO operational locale. Manned transfer from LEO to GEO is provided by a high-thrust two-stage chemical personnel orbital transfer vehicle (POTV).

Lunar material utilization Concept B, developed for in-space manufacturing, includes unique elements and innovative techniques and generally represents the proposals of Dr. Gerard O'Neill. Payload brought from earth includes transportation elements and their propellants, lunar mining equipment, material processing and fabrication equipment, personnal plus their habitats and supplies, and a small percentage of SPS components which cannot initially be manufactured economically in space.

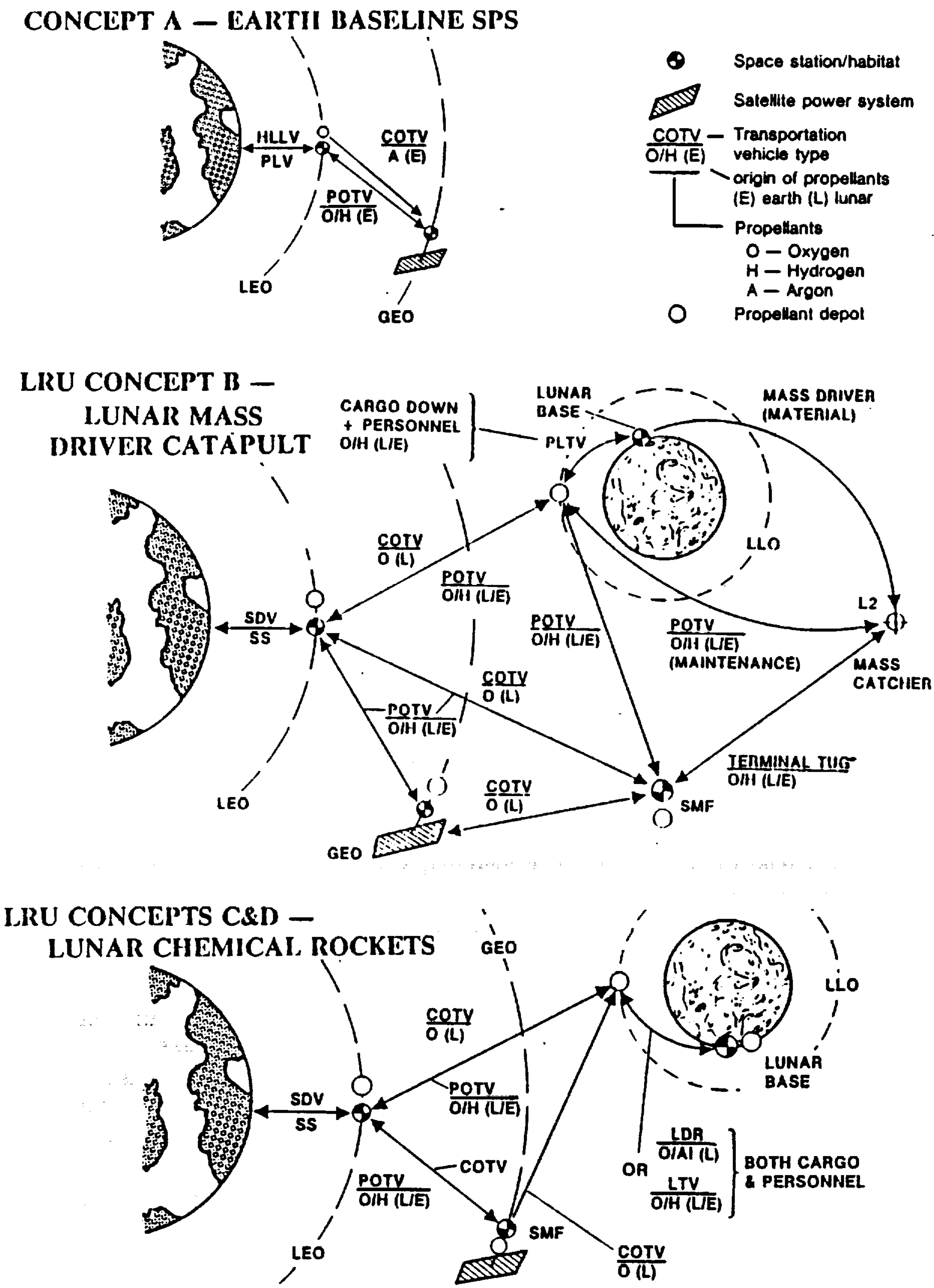


Figure 2-2. Space construction concepts.

Transfer of cargo from earth to LEO is accomplished by Shuttle-derived vehicle. The Space Shuttle is used for personnel. A relatively small logistics station is constructed in LEO which is used as a base to assemble transportation, processing, and habitation elements, and to integrate payloads for departure to their operational locales. All personnel transfer to other orbits is accomplished with a high thrust chemical POTV. Cargo transfer is provided via a low-thrust solar powered ion electric cargo orbital transfer vehicle (COTV) which uses oxygen propellant. For startup this oxygen is earth supplied, but once lunar mining facilities and SMF are operating all the oxygen propellant is derived from lunar resources. The COTV delivers lunar base facilities plus the personnel lunar transfer vehicle (PLTV) and its propellants to low lunar orbit, the mass catcher to L_2, and space manufacturing facility/habitation modules to their selected locale.

A lunar base is established by using the throttlable chemical PLTV to land material and personnel. Lunar base consists of mining equipment, a mass driver catapult to launch lunar material to L_2, living accommodations for personnel, a power plant (solar or nuclear), and supplies. The mass driver catapult consists of a linear electromagnetic accelerator which employs superconducting buckets to accelerate bags of lunar material to escape velocity. These buckets are slowed down after payload release and returned for reuse, so the only expenditure is electrical energy (Reference 5).

Lunar surface operations include material collection, screening, bagging and launch by the mass driver in a steady stream toward L_2. This material is retrieved by the mass catcher at L_2, accumulated in large loads, and subsequently delivered to the space manufacturing facility (SMF) by self powered catcher or terminal tug. At the SMF, this lunar soil is processed into useful structural materials, fabricated into components, and final-assembled into the solar power satellites. Although most of these manufacturing operations are highly automated, a significant number of personnel are required for final assembly, machine operation, maintenance and repair, plus support services. Completed earth SPS's are transferred to their GEO operating orbital location by COTV.

LRU systems Concepts C and D are similar to each other but constitute a significant departure from Concept B in two primary areas: material processing occurs on the lunar surface rather than in-space, and chemical rockets replace the mass driver catapult and mass catcher used for material transport from lunar surface into space. Concepts C and D have some transportation and support elements that are very similar to those in Concept B, such as earth launch and LEO station requirements. OTVs differ from those in B only by the sizing of cargo transfer stages and their propellant quantities.

The only significant difference between Concepts C and D results from the propellant used with chemical rockets for launching materials from the lunar surface. In Concept C, the lunar transfer vehicle (LTV) propellants are lunar derived oxygen and earth supplied hydrogen. For Concept D, the LTV derives all its propellants from lunar materials, and has therefore been designated a lunar derived rocket (LDR). Although many metals available in lunar resources could be used as LDR fuel, powdered aluminum was selected in conjunction with oxygen due to its relatively high performance when compared with calcium and combinations of lunar metals (Reference 6).

The Concept C/D lunar base is significantly larger since it now provides material processing and stock manufacturing in addition to mining and beneficiation. A chemical LTV or LDR is used to transport stock construction supplies to low lunar orbit where they are transferred to an ion electric COTV which uses lunar derived oxygen propellant for transport to the space manufacturing facility. Manufacturing of low density SPS components, large space structure fabrication, and final assembly are accomplished at the SMF which may be coincident to its product's use location in geosynchronous orbit.

Both the LTV and LDR are fully reusable. On the return trip from LLO to the lunar base, they transport personnel, life support supplies, replacement machinery parts, and processing chemicals. The LTV also carries its round trip hydrogen propellant which is tanked at the LLO depot. All other propellants for these vehicles are loaded on the lunar surface.

It is important to note that the Concept B mass driver catapult is not suitable for delivery of manufactured products due to its requirement for constant payload density and limitation on bucket volume. Therefore, processing and stock manufacturing for Concept B must be accomplished at the SMF. Alternatively, chemical lunar transfer vehicles must carry high density payloads which do not contain a significant percentage of unwanted material. Thus for Concepts C and D, processing and stock manufacturing are performed on the lunar surface to circumvent the inefficient process of utilizing large quantities of rocket propellant to lift unneeded material into space.

2.3.2 EARTH MATERIAL REQUIREMENTS DEVELOPMENT & COMPARISON. Earth material requirements were determined via development of material logistics scenarios for each space construction concept. A steady-state material logistics scenario assumes that all necessary facilities, vehicles, and personnel are in place and working. It defines the constant material flow needed to sustain the system's nonfluctuating output.

A common set of guidelines and transfer vehicle performance criteria were used for earth and lunar material requirements for earth baseline and lunar resource utilization options. These guidelines included an SPS lunar material construction fraction of 89.6 percent from the material requirements analysis (see Table 2-3), and assumed LRU personnel requirements to be approximately 3 times those needed for the earth baseline (480 at LEO plus 60 at GEO). Subsequent analyses showed this preliminary personnel estimate was reasonable, with total in-space personnel requirements of approximately 1600 people. Crew transport requirements were based on return to earth following a 90 day duty tour for Concept A, and up to 180 days for principal activity sites (SMF and lunar surface) in LRU Concepts B, C and D.

The earth material requirements for the earth baseline SPS reference scenario (Concept A) are presented in Figure 2-3. The material logistics flow shows 35.4 earth material units required for each unit of SPS completed in GEO. The vast majority of these, 33.1 units, are in the form of HLLV propellants. Total earth payload is 1.51 units plus personnel. All crew size estimates were based on the manufacture of one 10 GW SPS per year.

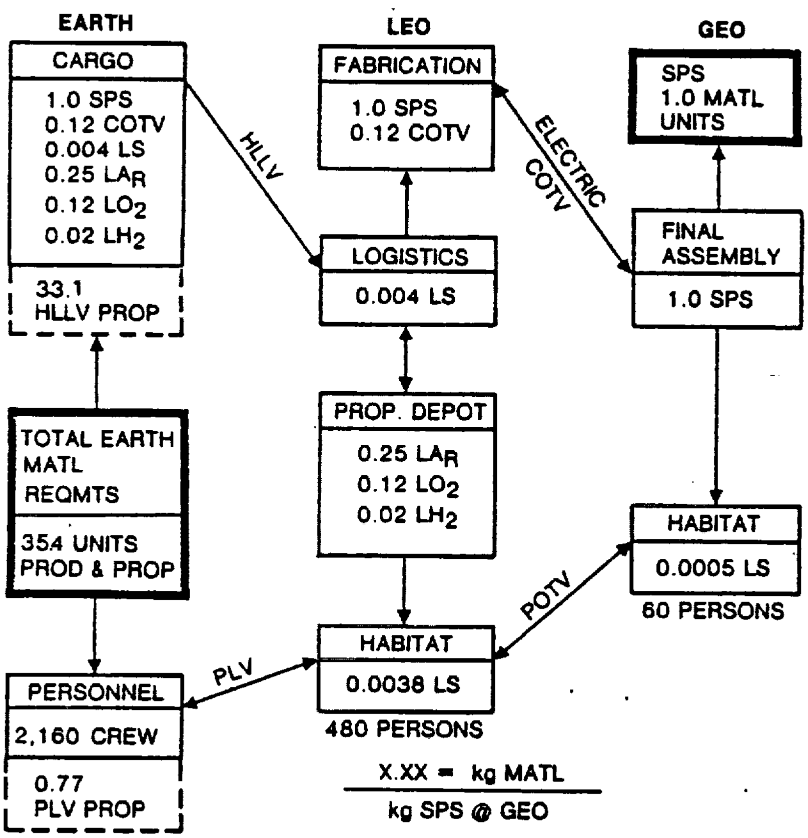


Figure 2-3. Earth baseline steady state material requirements.

The material requirement identified as "SPS" refers to satellite construction materials and components, and "COTV" refers to the ion thrusters used for LEO to GEO transfer of SPS segments. These ion thrusters comprised an expendable delivery method, and since they were not reused, the thrusters and their propellant tankage contribute to steady state earth material requirements. "LS" is life support supplies of food, water, and oxygen, while LA_R, LO_2 and LH_2 refer to propellant supplies of liquid argon, oxygen, and hydrogen respectively. LRU concepts also accounted for processing chemicals.

The earth material requirements (EMR) steady state logistics scenarios for the three LRU concepts are similar to that shown for the earth baseline, except for the added complexity due to additional activity locations and handling of lunar materials. All three LRU Concepts B, C and D offer substantial EMR reductions with EMR factors at 9%, 15%, and 10% of the earth baseline respectively. A comparison of the data derived from these three LRU concepts with the earth baseline (Concept A) data is contained in Table 2-4. The significance of these results is summarized for each of the LRU options in the following paragraphs.

Concept B offers the lowest earth and lunar material requirements. The earth launched cargo consists of only 0.138 kg/kg SPS, made up of 0.104 SPS components plus 0.034 of other supplies. The lunar material requirements are also low, since very little lunar derived propellant is consumed to transport lunar materials to the SMF (only LO_2 for catcher propulsion).

Concept C has the highest earth material requirements and intermediate lunar material requirements. The earth launched cargo consists of 0.241 kg/kg SPS, made up of 0.104 SPS components plus 0.137 of other supplies. The majority of these other supplies are hydrogen propellants required for the chemical lunar transfer vehicle (LTV) used to deliver lunar manufactured components to space. The LTV derives its oxygen propellant from lunar materials, which is the major contributor to increased lunar processing and mining requirements.

Concept D has intermediate earth material requirements and the highest lunar material requirements. The earth launched cargo consists of 0.154 kg/kg SPS, made up of 0.104 SPS components plus 0.050 of other supplies. A majority of these other supplies are processing chemicals needed to produce the large quantity of lunar propellants required for the lunar derived rocket (LDR). The LDR uses liquid oxygen and powdered aluminum obtained from the moon as its propellants. The requirement for aluminum is the driver for Concept D's very large lunar material mining and processing requirements.

These steady state logistics scenarios were also employed to develop EMR sensitivity information for changes in input data. In addition to basic EMR and LMR sensitivity to the percentage of lunar resource utilization in SPS construction, sensitivity data was

Table 2-4. LRU concept comparison with earth baseline.

(kg OF MATERIAL / kg OF SPS @ GEO)	SYSTEMS CONCEPT			
	A Earth Baseline	B Mass Driver	C Conventional Rocket	D Lunar Derived Rocket
Total Earth Material Requirements	35.4	3.211	5.289	3.706
Total Payload	1.52	0.138	0.241	0.154
Earth Launch Propellants	33.9	3.073	5.048	3.552
Total Lunar Material Requirements	—	1.715	3.491	5.568
Products		1.112	1.756	3.037
Slag	—	0.603	1.735	2.531

obtained on COTV type (ion electric or MDRE), vehicle stage efficiencies, chemical loss fraction during processing, oxygen recovery from lunar soil, and personnel support requirements. Two significant results were obtained from this analysis:

- EMR is sensitive to the percent of SPS derived from lunar resources. A 10 per~~:~~t decrease in LRU results in EMR increases of 52, 34, and 49 percent for Concepts B, C, and D respectively.

- EMR is relatively insensitive to crew size, with doubled personnel requirements resulting in EMR increases of 27 and 17 percent for Concepts B and C.

2.3.3 ELEMENT DEFINITION. Description of lunar resource utilization major system elements was organized into three categories: Processing and Manufacturing, Transportation, and Infrastructure elements which are represented by the examples depicted in Figure 2-4. Element sizing was based on requirements derived from steady state operations material logistics scenarios to support production of one 10 GW SPS per year. The majority of system elements were scaled from existing conceptual definitions available in previous and current NASA/Industry studies (References 3, 7, 8, 9, 10 and 11).

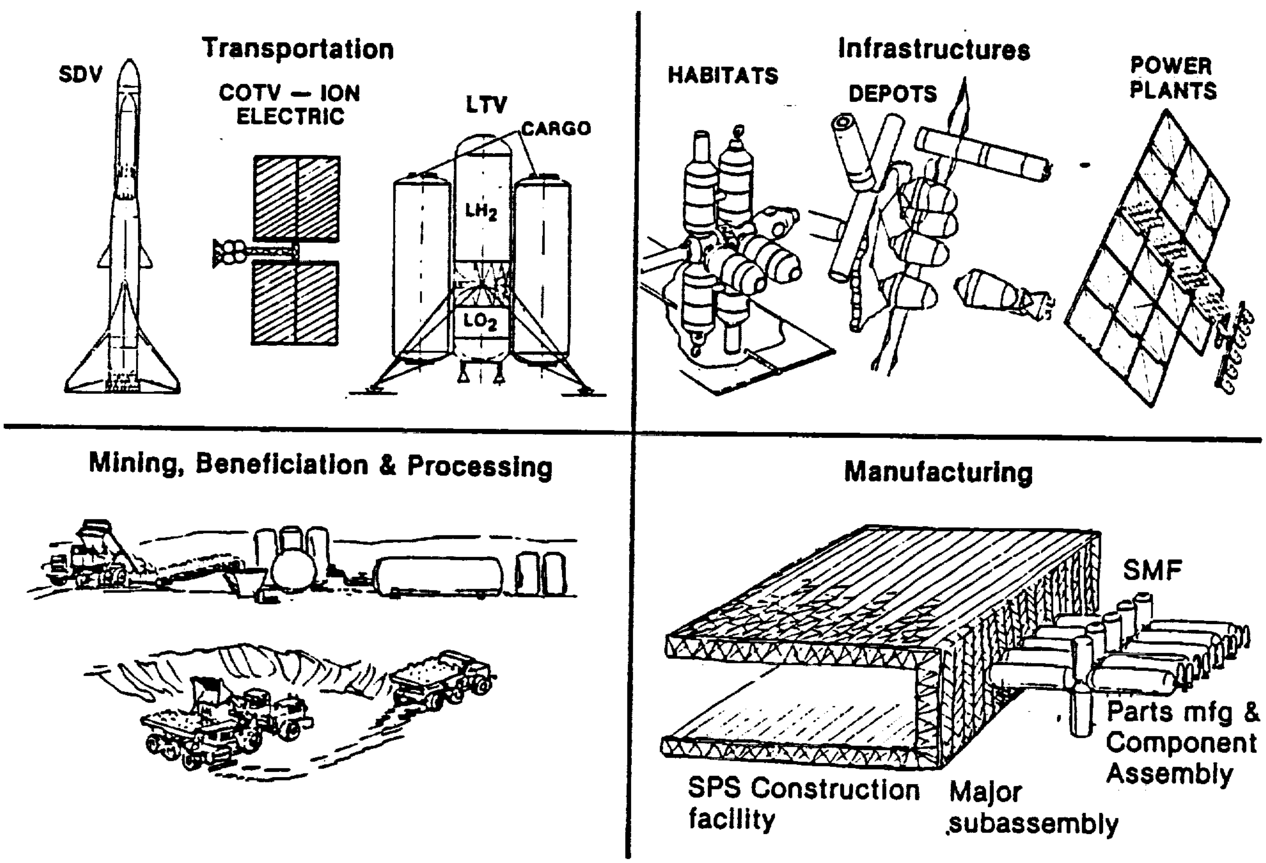


Figure 2-4. Representative LRU system elements.

PROCESSING AND MANUFACTURING SYSTEM ELEMENTS — Lunar resource utilization concept feasibility requires that useful materials are available on the moon. Appropriate lunar materials must be obtained to provide glass, silicon, aluminum, iron, and oxygen from which the fifteen SPS product groups are manufactured. Facilities are required to process raw lunar material into these useful constitiuents, manufacture the components, and assemble the satellite.

The diagram in Figure 2-5 identifies the lunar material flow, processing steps and manufacturing steps required to transform raw lunar material into a complete 10 GW solar power satellite.

MINING — Due to the sandy nature of lunar soil, the least expensive method of mineral collection would undoubtedly be by surface mining, using scraper-loaders or ditch diggers and transporting soil via surface vehicles or conveyors to a nearby beneficiation of space transportation facility. Automated material collection would be appropriate due to the repetitive nature of surface mining activities, and since long term exposure on the lunar surface may subject workers to harmful radiation during periods of solar flare activity (Reference 12).

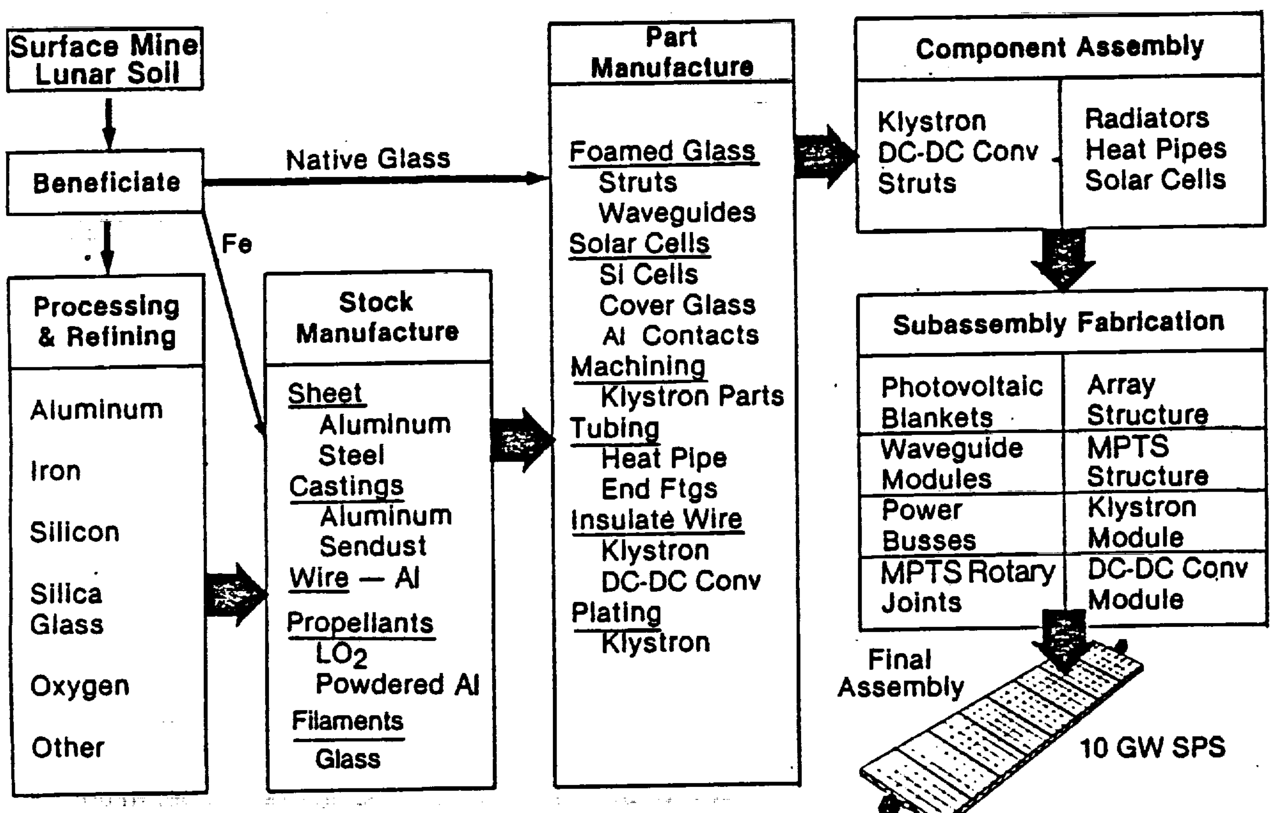


Figure 2-5. Scope of processing and manufacturing operations.

BENEFICIATION — Free iron and glass particles are two materials which may be separated from lunar soil by magnetic and electrostatic means, respectively. Fine particles of glass constitute a significant percentage of the finer fractions of lunar soil, constituting 30 to 50% by weight of the 5–10 μm size range. The recovery of the free iron in lunar soil by means of magnetic separation could provide a significant proportion of this metal's requirements for the SPS. By magnetic separation, each 100,000 tons of lunar soil may yield 150–200 tons of iron (Reference 13).

PROCESSING — A lunar or space based metals and minerals industry should be based upon the naturally occurring lunar and space environments which are characterized by high vacuum, low gravity, and abundant solar energy. Earth based metals industry employs pyrometallurgy or hydrometallurgy for processing, but the coal, oil, gas, water, and many of the chemicals required are not abundant on the moon. Direct electrolysis of molten lunar soil appears to offer promise as an initial processing step, followed by chemical refining. Electrolysis of the molten material results in oxygen being released at the anode and silicon plus metals at the cathode which can be refined by chemical processing. Many processes appear to be suitable for lunar material processing, and subsequent experimental evaluation will be required to identify the most cost effective technique (References 14 and 15).

METAL SHAPE PRODUCTION PROCESSES — The standard earth practice of melting aluminum in electric furnaces, casting into ingots, followed by reheating the ingots and rolling them down into plate and sheet form does not lend itself to lunar or SMF application. This practice is not only wasteful of energy due to repeated heating and cooling of the metal, but also involves a considerable amount of large and heavy operating equipment such as electric furnaces and power supplies, ingot molds, rolling mills and supporting equipment. As an alternate, vapor phase deposition of aluminum and iron is proposed. Extensive work has been done on developing high-rate physical vapor deposition of metals and alloys and evaluating the mechanical properties of metals so deposited. Review of work performed thus far indicates that the mechanical properties of vapor deposited metals and alloys can be comparable to those of the same metals made by casting, rolling, and annealing (Reference 16).

In summary, the material flow shown in Figure 2-5 proceeds through the following steps. Lunar soil is beneficiated to recover free iron and glass fractions. The remainder is processed by electrolytic and/or chemical means to extract oxygen, silica and metals. The silica is further processed into clear silica glass sheet for solar cell substrates and covers. Silicon is purified to semiconductor grade material and grown into ribbons for fabrication into silicon solar cells. Aluminum and iron are processed by electron beam vapor deposition, casting, and other means into sheet, wire and other required stock forms and then fabricated into shapes and components required for solar power satellite construction. The native lunar glass is combined with sodium sulfate and carbon from earth to manufacture foamed glass components.

Based on these production processes, facility mass and power estimates were obtained for stock production, parts manufacturing, component assembly, and solar cell panel production to support construction of one 10 GW SPS per year. Insofar as possible, these manufacturing and component assembly facilities would be automated, with full use made of robotized materials handling, assembly and transport equipment. Results of this activity showed that solar cell panel production facilities dominate both mass and power requirements, accounting for more than 90 percent of total SMF capability. Solar cells for one 10 GW SPS comprise an area of approximately 100 km^2, which is four orders of magnitude greater than current U.S. production capability. Since each 10 GW SPS requires approximately 15,000 tons of solar cell grade silicon and 37,000 tons of 50-75 μm thick silica glass, it is evident that silicon solar cell production is a critical and pacing item in the SPS. Whether produced on earth or in a space manufacturing facility, a major effort will be required to both develop production processes and to expand these processes to the level capable of supporting a 10 GW/ year SPS program (Reference 17).

TRANSPORTATION SYSTEM ELEMENTS — Ten basic vehicle types for the seven principal LRU transportation routes were defined. In addition to this basic vehicle definition task, trade studies and investigations of fundamental transportation issues were conducted. The results of these investigations are summarized in the following paragraphs.

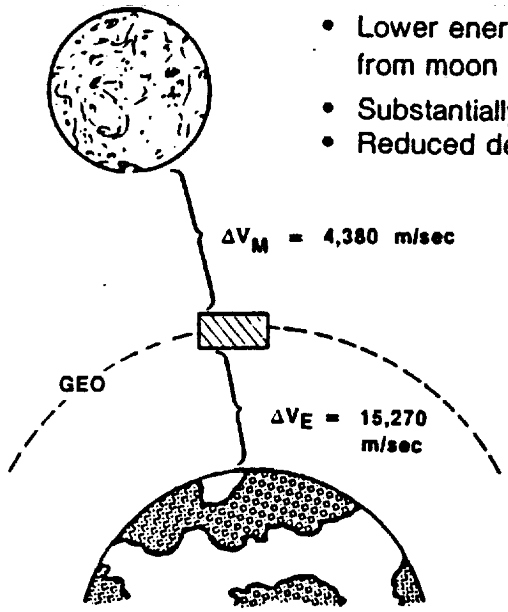
Since LRU concepts require earth launched payload 9 to 15 percent of that for the reference baseline, a smaller reusable launch vehicle such as a shuttle derived vehicle (SDV) was a suitable substitute for the heavy lift launch vehicle (HLLV). The SDV postulated for this study was based on the current Space Shuttle Transportation System (SSTS) with the following modifications: 1) The solid rocket boosters (SRB's) were replaced by liquid propellant (LO_2/C_3H_8) booster. This booster was a lox/propane version the GDC B17E-1 flyback booster from the SSTS Phase I study. The booster would not have airbreathing flyback capability but would land down range and be ground transported back to the launch area. 2) The external tank would be modified to accept boost loads through the base ring rather than the current SRB side attachment points. 3) The Orbiter would be replaced by a cargo pod and a ballistic returnable propulsion module. The SDV had a payload capacity of 200 T, and a launch frequency of one flight every 3rd day was required to satisfy LRU scenario earth cargo delivery.

Two candidate low thrust propulsion systems were evaluated for cargo transfer in space; ion bombardment electric thrusters using oxygen propellant, and a mass driver reaction engine (MDRE). Although both concepts appear technically feasible and utilize propellants attainable from lunar resources, the ion electric propulsion device was selected as the representative system for this study because: 1) Ion electric technology development (with argon) is more mature than MDRE technology development. 2) The ion electric specific impulse is approximately 6 times greater than that predicted for MDRE. This combined with a projected lower inert mass for the ion electric COTV results in significantly lower propellant requirements. 3) A lunar derived propellant, oxygen, should be acceptable for use with an ion-electric COTV. This reduced somewhat the MDRE advantage of using any available waste material as reaction mass. 4) Study personnel felt strongly that if the MDRE were used, it should employ a material such as oxygen for reaction mass to eliminate the safety concern of solid high velocity exhaust particles in the vicinity of habitats, manufacturing facilities, and SPS's. Thus similar lunar propellant processing requirements are imposed for MDRE or ion electric COTV, since both use oxygen propellant.

LRU Concept B employed a mass driver catapult on the lunar surface and a mass catcher in the vicinity of L_2 to effect lunar material transfer. Subsequent transfer of accumulated catcher material from L_2 to the SMF was to be accomplished via a free trajectory with recovery at the SMF performed by a chemically propelled tug. Providing increased mass catcher ΔV capability allows its direct transfer to the SMF and permits deletion of the tug. This eliminates problems associated with retrieval of uncontrolled massive payloads; it also reduces or eliminates the need for manned maintenance at the catcher site. An obvious drawback would be a longer time off station for the catcher, or the requirement for several catchers. Both high and low thrust propulsion systems would be required for an integrated mass catcher/tug. The suggested catcher low thrust propulsion system was O_2 ion electric for station keeping, momentum absorption and basic transfer, powered by a nuclear source to preclude damage by near misses. A relatively high thrust LO_2/LH_2 ACS was proposed for initial material stream acquisition and rendezvous maneuvering at the SMF.

The idea of using lunar materials for in-space construction was suggested by the lower energy requirements needed to transport material from the lunar surface to a point in deep space, as compared with delivery from the earth's surface to the same point. This energy difference has been expressed as gravity wells (4,000 miles deep for earth, 180 miles deep for the moon), and as the ratio of potential energy per unit mass for earth and moon, i.e., 22:1. These ratios express relative energy requirements to escape the gravitational influence of the earth and moon. The point of interest in space for the LRU study is geosynchronous orbit, which remains within the gravitational influence of both bodies. Another method of expressing the relative transportation requirements is by ΔV, the velocity increment which must be imparted to transfer payload from one point to another. The ΔV's shown in Figure 2-6 have been determined by realistically assuming that two vehicles should be used from each body's surface to GEO, and that payload transfer from one vehicle to the other will occur in a low stable orbit. Based on these assumptions the energy ratio to geosynchronous orbit is approximately 12:1.

Another method of expressing this energy ratio is as propellant mass requirements for delivering an equivalent payload. In this case the propellant mass is strongly influenced by the vehicle propulsion systems selected. Efficient systems (high Isp) will have lower propellant requirements than inefficient systems. To demonstrate this effect, propellant mass ratios were calculated for the three LRU concepts developed by this study. Earth launch (SDV with chemical propellants) and in space transfer between



- Lower energy requirements for delivery of material from moon to GEO than from earth to GEO
- Substantially reduced propellant requirements
- Reduced depletion of earth resources

$$\frac{\Delta V_E}{\Delta V_M} = 3.5$$

$$\frac{E_E}{E_M} = \frac{\frac{1}{2}\, m\, \Delta V_E^2}{\frac{1}{2}\, m\, \Delta V_M^2} = 12.2$$

$$\frac{\text{Propellant}_E}{\text{Propellant}_M} = 10 - 150$$

depending on transporatation system elements selected

Figure 2-6. LRU transportation benefit.

LEO and GEO, LLO and GEO, and L_2 and GEO (ion electric COTV with oxygen propellant) were common to all three concepts. The vehicles employed for lunar surface to LLO transfer differ; electrically driven catapult for Concept B, conventional hydrogen/oxygen for Concept C, and aluminum/oxygen rocket for Concept D. The earth/lunar propellant delivery ratios for these three concepts are; LRU Concept B 146:1, LRU Concept C 27:1, and LRU Concept D 10.5:1. An important ancillary criterion is propelland origin. Concept C has a higher earth/lunar propellant delivery ratio than Concept D, but some of C's lunar escape propellant must come from earth (hydrogen), while all of D's lunar escape propellant is derived from lunar resources.

INFRASTRUCTURE SYSTEM ELEMENTS — The best all-encompassing definition of infrastructure was obtained by exclusion; i.e., infrastructure included every lunar surface or in-space element that was not part of the material processing/fabrication system or the transportation system. The major elements required for lunar resource utilization were collected into three categories; habitats, propellant depots, and power plants. Obviously a great many implementation options exist for each major element. Most of these infrastructures have been studied extensively by NASA and their major aerospace contractors. This data was used to define and size the elements needed.

Living quarters are required at each major lunar resource utilization activity location, and temporary shelters may be needed at unmanned equipment installations to accommodate maintenance personnel. Requirements for manned space stations are characterized by population size, stay time, and the requirements for pseudogravity and radiation protection. Habitats fell into four general categories: 1) small space stations (10 to

100 people) which have been studied extensively by NASA and industry since the early 1960s. 2) Temporary shelters (~10 people) which provide environmental protection and cramped personnel comfort facilities (bed, board and bathroom). Their conceptual design and programmatic definition was easily derived from space station study data. 3) The lunar base concept, also studied by NASA, except these bases were configured primarily for scientific research with crew sizes from 12 to 180. Larger lunar base habitats were proposed during the 1977 Ames summer study which make use of Shuttle external tanks. 4) Large habitat concepts (~1000 people) must be a compromise between existing zero-g space station designs which were much too small, and proposed 1 g permanent space settlement concepts which were too large. A concept which used clustered ET hydrogen tanks for pressure shells with internal furnishings and operational equipment brought up by Shuttle in kit or modular form and installed on-orbit was favored. A habitat requirements summary is presented in Table 2-5.

Table 2-5. Habitat sizing requirements summary.

Habitat Population	LEO	GEO	SMF	LLO	Lunar Surface Base	Lunar Surface Remote	Total Personnel
Reference Earth Baseline							
— Concept A	480	60	—	—	—	—	540
LRU Concept B	60	60	1400	(T)	60 +	(T)	1580
LRU Concept C&D	60	1200		(T)	400	—	1660

(T) = Temporary Shelter

Propellant Depots are required at every LRU system concept logistic center where cargo and/or personnel must be transferred to a different transportation vehicle. For the earth baseline (systems Concept A) the only depot requirement is at LEO. The lunar resource utilization options all require LH_2/LO_2 propellant supplies for POTV refueling and LO_2 for COTV refueling at LEO, LLO, and the space construction facility/GEO. Lunar surface propellant requirements are dependent on the material launch technique employed. In-space depots included a basic platform structure, propellant modules and their berthing docks, propellant transfer plumbing, avionics, and reliquefaction equipment. Reliquefaction equipment was included as part of the depot to eliminate propellant boil-off losses. The lunar surface propellant facility for systems Concepts C and D must liquefy gasseous oxygen produced by anorthite processing so that it can be consumed by the LTV and easily transported and stored in the various orbiting depots. Systems Concept B employed a mass driver catapult on the lunar surface to supply an orbital processing and manufacturing facility with raw lunar material. Although the total oxygen propellant requirements were reduced for Concept B due to the mass driver, a substantial amount was still required for POTV oxidizer and COTV propellant. An orbital liquefaction depot was configured to supply this oxygen.

Power plants are required to supply electrical energy for lunar surface operations and space manufacturing facilities. Other habitats and all in-space depots incorporated their own photovoltaic power supplies. A nuclear fission Brayton cycle was assumed for supplying lunar base electrical power. This choice was influenced by the 330 hour lunar night which imposed a severe mass penalty for solar energy storage systems. Attractive alternatives to nuclear Brayton include a lunar surface mounted photovoltaic system with orbital reflectors to reduce storage requirements, or a magnetogasdynamics power system. Photovoltaic power systems were recommended for all space manufacturing facilities.

2.3.4 MATERIAL CHARACTERIZATION. SPS construction material was characterized in terms of its composition, packaging, and the quantity transferred between the mining location on the moon and the manufacturing location in-space. Materials are required from both the earth and moon. Lunar material requirements were developed based on the updated quantity of 105,650 T needed for completed SPS parts plus the lunar derived propellants needed to deliver lunar and earth supplies. Propellant requirements were obtained from the steady state material logistics scenarios. The following assumptions were used in obtaining these material requirements.

1) The maximum recovery of any single element from lunar soil is 50 percent.

2) Highlands soil element percentages were used due to the quantity of aluminum (relative to iron) required.

3) Beneficiated iron recovery via magnetic separation of 0.15 percent was used. Remaining iron requirements were provided by electrolysis of molten lunar soil and subsequent refining.

4) A 5 percent material loss due to initial beneficiation was used for Concept B. This removal of the large lithic fragments occurred prior to material transport to the SMF via mass driver catapult.

Lunar materials needed for each LRU systems concept are listed in Table 2-6. It is interesting to note that each concept has a unique element recovery requirement which determines the material mined quantity. Silicon for SPS solar cells in Concept B, oxygen for LTV and COTV propellant in Concept C, and aluminum for LDR fuel in Concept D dictate total material requirements. Sufficient quantities of other elements are available in the mined material so that element recovery requirements rarely exceed 35 percent (only native glass in Concept B).

Earth material requirements include various SPS components such as electronics assembles and special metal parts, alloying materials, plus cooling fluids and processing chemicals. Total annual earth supplied material was estimated at 12,490 T, of

Table 2-6. Lunar material requirements per 10 GW SPS.

Total Lunar Material Mined	Sys Concept B Mass (T) 384,700	Sys Concept B Element Percent Recovered	Sys Concept C Mass (T) 507,800	Sys Concept C Element Percent Recovered	Sys Concept D Mass (T) 1,145,900	Sys Concept D Element Percent Recovered
Native Glass	34,690	47	34,690	34	34,690	15
Beneficiated Fe	550	27	760	19	1,720	8
Processed Fe	3,910		3,700		2,740	
Processed O_2	39,250	27	105,510	50	174,500	35
Processed Si	34,830	50	34,830	35	34,830	15
Processed Al	12,280	28	12,280	20	73,900	50
Total useful material required	125,510	33	191,770	38	322,380	28

which only 4 percent represented unrecoverable cooling and processing supplies. Specific emphasis was placed on defining requirements for water, since most earth manufacturing operations utilize large quantities of H_2O for cooling, washing, and other purposes. Due to the processing techniques postulated for in-space manufacturing, very little water is required. Estimated annual H_2O resupply due to processing and cooling system losses was approximately 300 T. An initial SMF water supply of 1000 T was estimated. Additional water for personnel drinking and washing was included in the 0.8 T/year of consumables allocated for each space worker.

Material characterization for Concept B involves lunar surface activities which are limited to material mining, beneficiation, packaging, and launch. Additional beneficiation and all SMF product and propellant related processing and manufacturing operations occur at the space manufacturing facility. This results in an accumulation of waste material (slag) at the SMF, which is useful as radiation shielding. This transfer of large quantities of excess material from lunar surface to SMF can only be justified if a catapult and retrieval system like the mass driver/mass catcher is employed. Conventional rocket transfer methods would result in unacceptable propellant consumption requirements.

As depicted in Figure 2-7, lunar surface operations consist of mining, and beneficiation to remove the large lithic fragments and separate out native lunar glass. This native glass is used to produce the woven glass bags which serve as packaging for mass driver "payloads." Some limited chemical refining may be required for the glass bag manufacturing operation, and if an aluminum coating for electrostatic guidance is desired on the bags, some processing will also be necessary. Lunar soil is packed into these bags and catapulted from the moon. These mass driver payloads are retrieved by the mass

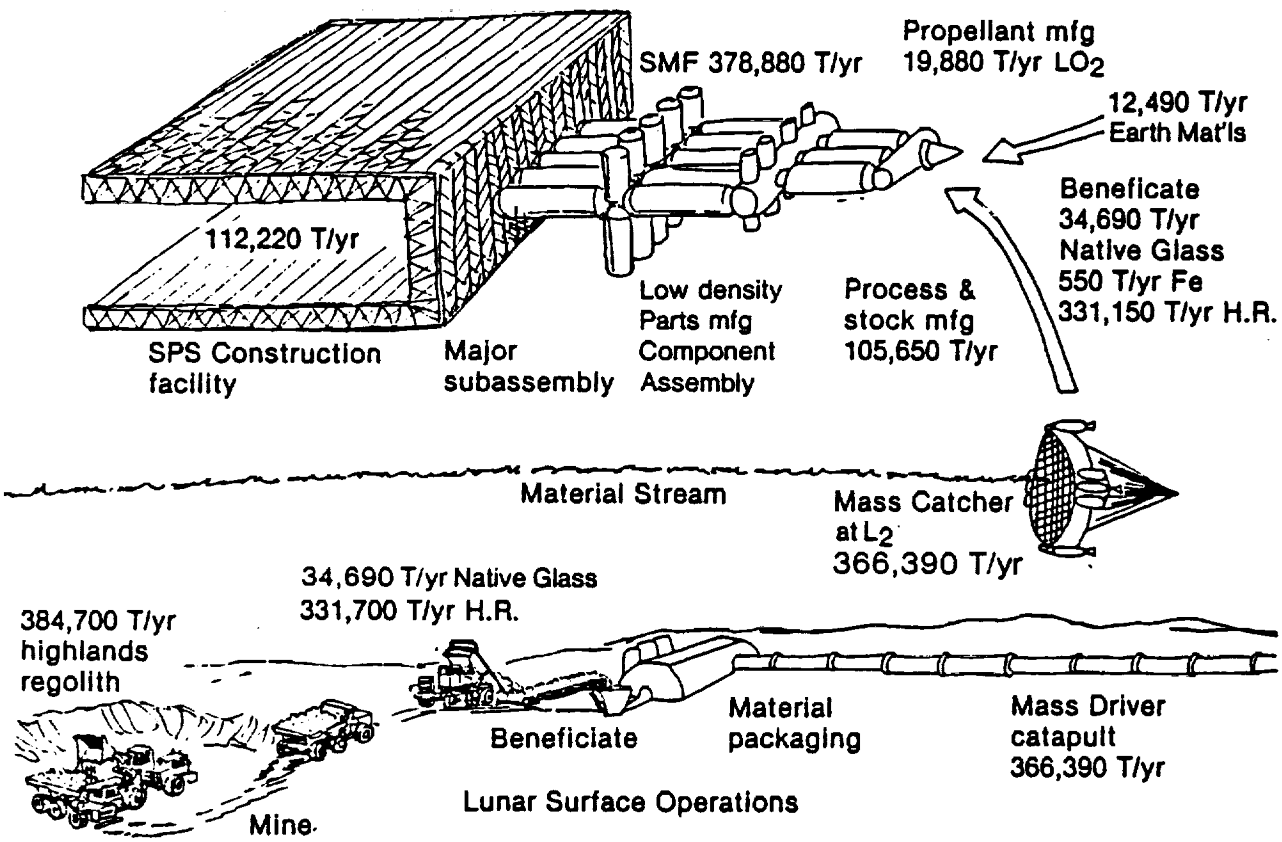


Figure 2-7. Material characterization for LRU Concept B.

catcher, an action which results in rupture of the woven glass containment bags. A catcher ion-electric propulsion system, using oxygen propellant supplied by the SMF, transfers accumulated material to the SMF.

At the SMF, beneficiation operations are repeated to recover the native glass bag material and seperate out free iron. All subsequent processing, propellant manufacturing, stock production, parts manufacturing, and SPS fabrication occur at the SMF. The recovered native glass is reused to produce foamed glass structural members for SPS.

Of the original 384,700 T mined on the moon, 18,310 T remains on the lunar surface and 366,390 T is delivered to the SMF. From this is produced 125,530 T of useful products and 240,860 T remains as slag. Unrecoverable losses during subsequent manufacturing and assembly operations result in an additional accumulation of 5,920 T, some of which is from earth delivered materials. Thus total SMF slag production is 246,780 T per SPS. Shielding requirements for the SMF habitat have been estimated at 85,500 T, approximately a 4 month slag supply at the assumed production rate of one SPS/yr.

Material characterization for Concept C involves processing on the lunar surface to remove most of the unwanted material (slag), prior to space delivery with chemical rockets. This circumvents the inefficient process of utilizing large quantities of rocket propellant to lift unneeded material into space. Lunar surface processing involves beneficiation to recover free glass and iron. Separation of aluminum or iron rich soils is not required for Concept C since the driving element recovery requirement is oxygen (for propellant), which is equally prevalent in all soils. For Concept D, additional beneficiation to obtain aluminum rich soils would be desirable, since aluminum propellant needs are the key driver.

As shown in Figure 2-8, lunar surface processing includes production of metalurgical grade iron and aluminum (some earth alloying materials may be added), some metalurgical grade silicon (for high quality silica glass), highly purified silicon (for solar cells), and liquid oxygen. Native lunar glass for subsequent manufacture of foamed glass is obtained directly from beneficiation of the lunar soil. Of the original 507,800 T highlands regolith, 191,790 T useful material is retained and 316,010 T remains on the lunar surface as slag.

Lunar surface stock manufacturing output consists of high density metal products including rolls of 1m wide aluminum sheet and 7 cm and 16 cm wide steel sheet, coils of aluminum wire, and aluminum and sendust castings. Nonmetallic products include spools of glass fiber and marbles of high purity SiO_2. These products, plus bags of native glass,

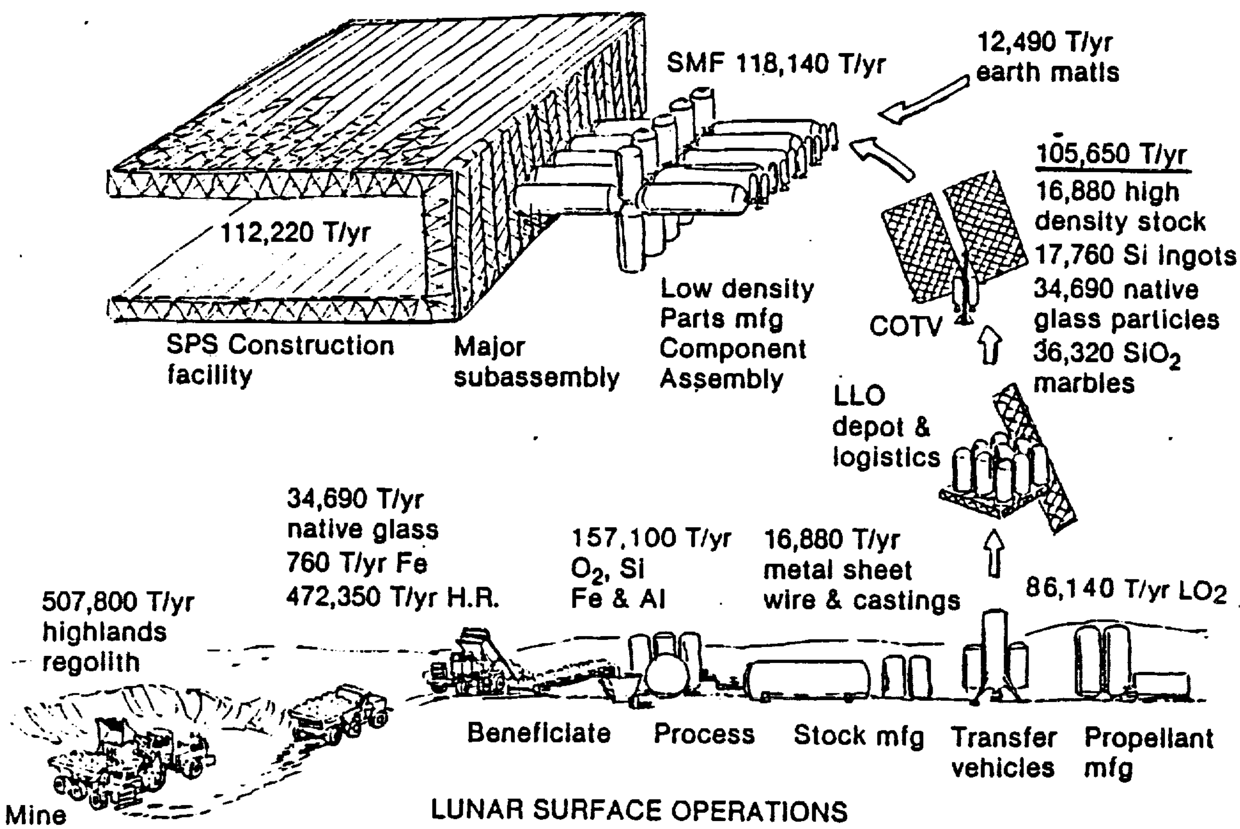


Figure 2-8. Material characterization for LRU Concept C.

ingots of refined silicon, and containers of liquid oxygen comprise the LTV payload. All payload items are loaded into LTV payload canisters of 155 T capacity and launched in pairs. Most of the LO_2 is used as LTV propellant, only 24,000 T is payload for delivery to LLO. In LLO, the containerized payloads are transferred from LTV to COTV for the trip to GEO. LO_2 payload is distributed to GEO and LEO depots by COTV, and some remains at the LLO depot. At the SMF in GEO, dense materials and products are manufactured into low density parts, components, and subassemblies; and fabricated into the SPS. Many of these parts should be manufactured only at the SMF due to their very low density (foamed glass structure) or fragility (silicon solar cell panels). Delivery of these manufactured parts from the lunar surface would result in extremely difficult packaging and handling problems.

LRU Concept D is similar to Concept C except a larger quantity of regolith is mined, beneficiated, and processed on the lunar surface to supply the oxygen and aluminum LDR propellants required to launch the 105,650 T of SPS construction materials into low lunar orbit.

2.3.5 START-UP. Start-up for any LRU concept involves delivering all space facilities, vehicles, initial supplies, initial propellants, and personnel to their proper locations, and placing them on operational status to support steady state production. Start-up phase accomplishment for an in-space manufacturing scenario may have a significant effect on total program cost due to its early funding requirements. It may also influence the design and production requirements for launch or orbital transfer vehicles, since start-up material transfer rates may exceed those for steady state operations.

The equipment which must be delivered from earth into space and placed on operational status includes lunar material mining and beneficiation equipment, processing and refining facilities, stock material and component manufacturing facilities, SPS subassembly and final assembly fixtures, propellant depots and liquefaction facilities, habitats and power plants. Vehicles and propellants for delivery of these facilities must also be delivered from earth. We have conservatively assumed that <u>all</u> propellants required during start-up operations are delivered from earth. In addition, all initial depot propellant supplies to support steady state operations are also obtained from earth, except for SMF depot oxygen in Concept B, and the LLO depot oxygen in Concepts C and D. Some of these start-up and initial propellant supplies could conceivably be derived from lunar resources during the latter part of the start-up period, significantly reducing earth payload requirements.

Figure 2-9 summarizes the start-up mass requirements for LRU Concept B. Start-up for this concept requires a total earth launched payload of 128 kT, and if constrained by the steady state transportation vehicle fleet size, requires at least three years to accomplish. The earth launched cargo has been separated into two categories; facilities and propellants. Facility mass totals 89,600 T, or 70 percent of total payload mass. The remaining payload consists of propellant, which can be separated into that required for facility transfer, 29,350 T, and initial propellant supplies stored in depots to support the initiation of steady state operations, 9,050 T.

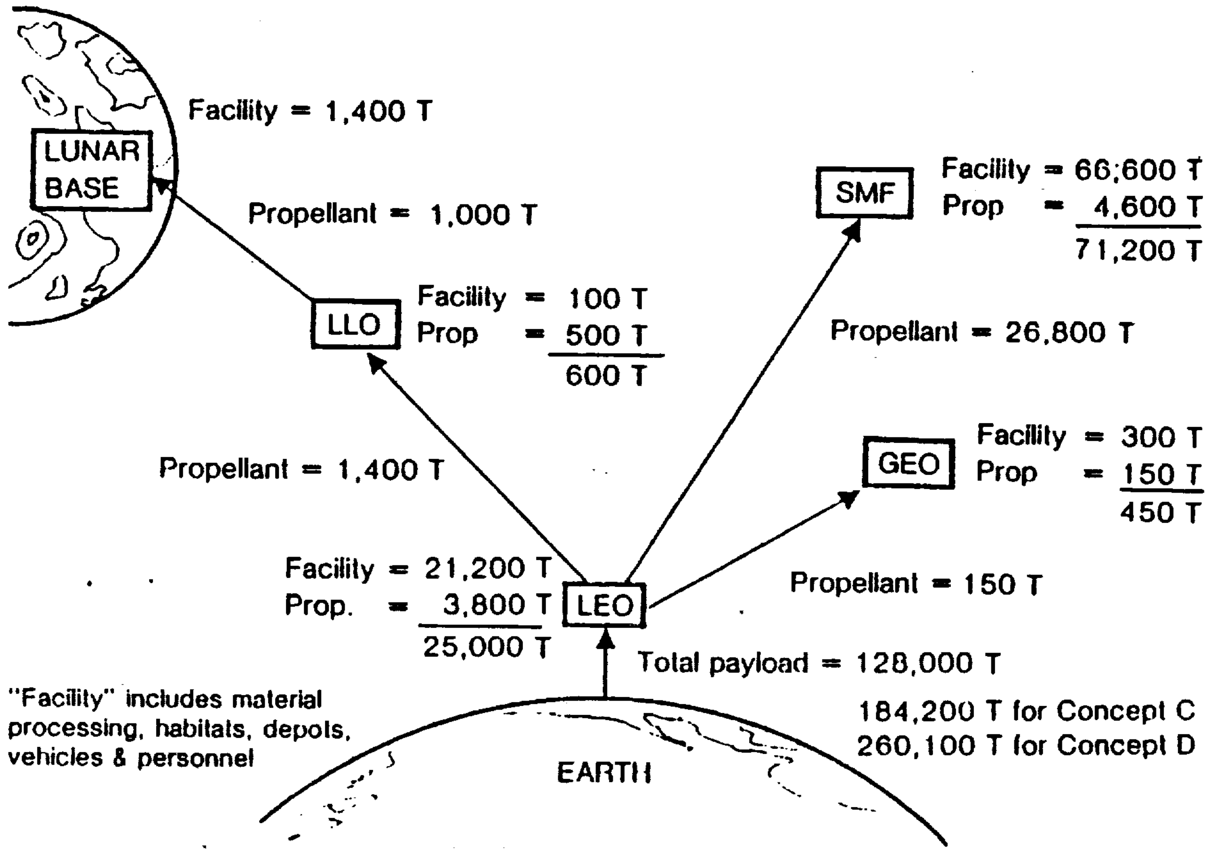


Figure 2-9. Start-up mass estimate for LRU Concept B.

Start-up mass requirements for LRU Concepts C and D are greater than those for Concept B since additional lunar material is processed to produce propellants. The facility delivery leg from LEO to SMF is eliminated for Concepts C and D, however, since the SMF is located at GEO.

Total earth launched payload for start-up plus steady state operations is plotted as a function of time in Figure 2-10 for the earth baseline (Concept A) and LRU Concepts B, C and D. Start-up payload requirements for LRU Concepts B, C and D were obtained from Figure 2-9 and occur over a three year period. Start-up for Concept A is equivalent to 61 HLLV flights in one year, or 26 kT, per the NASA-JSC earth baseline brochure.

Steady state earth payload requirements were obtained for 1 SPS/year from the steady state material logistics scenarios developed for each concept and are 147.7, 13.6, 23.7, and 15.2 kT/year for Concepts A through D respectively.

The earth launched payload cross-over occurs for all three LRU concepts during year two of steady state operations or a maximum of five years from initiation of LRU start-up. Total earth launched payload for LRU Concept C is 20 percent of the earth

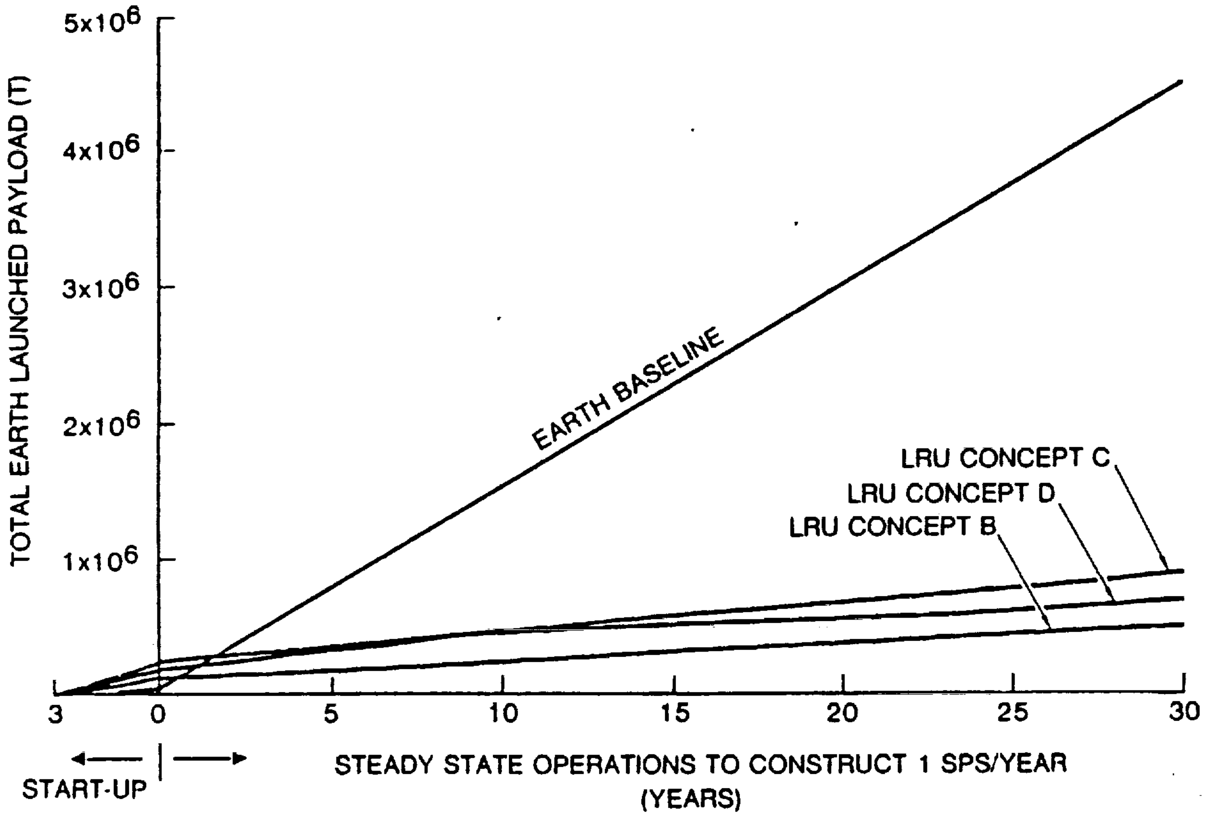


Figure 2-10. Earth launched payload comparison.

baseline after 30 years of operation. This difference is significant even though lunar resources are being recovered and utilized with Concept C and not A. The earth launched payload requirement for lunar resource concepts does include all non-terrestrial material utilization support elements such as processing chemicals, personnel, life support provisions, and supplies. The lowest earth payload requirement is for LRU Concept B at 12 percent of the earth baseline after 30 years of operation.

2.4 ECONOMIC ASSESSMENT

This section considers the economic aspects of construction alternatives to determine if lunar resources utilization has the potential to be a more cost effective approach than the Earth Baseline. The economic analysis portion of the study was divided into four major task areas: Cost Analysis, Sensitivity Analysis, Uncertainty Analysis, and Program Funding Schedule and Present Value Analysis.

Cost Analysis — The purpose of the cost analysis was to compare the program costs of each LRU concept with the Earth Baseline Concept costs provided by NASA/JSC. In order to obtain consistent comparisons a WBS was developed that was compatible with all concepts. The Earth Baseline costs were categorized into this WBS for comparison with the study generated LRU concept costs. The approach to total program cost determination for the LRU concepts was to first develop the costs of the primary elements (i.e., processing and manufacturing, transportation, and infrastructures) and then assemble them into the WBS for comparison with the baseline, Comparisons were then made in order to explain major cost differences and to identify areas of uncertainty. Finally, a determination was made of the nominal thresholds where lunar resource utilization becomes more cost effective. Subsequent study tasks, including the cost sensitivity, uncertainty and present value analyses, used the nominal costs determined in this task as a base.

Sensitivity Analyses — A major assumption used in determining LRU Concept costs was a vertically integrated manufacturing chain, owned and operated by a single entity. This assumption resulted in a manufacturing cost savings equivalent to the expected transportation savings. This manufacturing cost saving may not have been found had the LRU manufacturing chain been more like the Earth Baseline Chain with its many owners and inefficiencies. The purpose of the sensitivity analyses was to determine the economic thresholds if manufacturing costs for each LRU concept were the same as the Earth Baseline. If the assumption regarding the LRU manufacturing chain is erroneous, this sensitivity analysis shows the effect on the economic threshold points.

Uncertainty Analysis — The uncertainty analysis complements and expands the cost and sensitivity analyses tasks. Nominal costs represent point cost estimates which are based on historical data, direct quotes, analyst judgment and extrapolations of previous cost estimates. There is a great deal of uncertainty associated with these point cost estimates in the areas of supply/demand shifts, unknowns in the space/lunar based manufacturing chain and the state of definition of the hardware and program characteristics. The uncertainty analysis is an attempt to quantify that uncertainty. It provides a measure of confidence in our ability to accurately compare future conceptual projects and significantly affects the economic threshold point where the LRU concepts become cost effective.

Program Funding Schedule and Present Value Analysis — The timing of required expenditures and the present value of each program's total cost were determined to provide additional economic comparisons of the concepts. Nominal cost estimates consider the magnitude of cost but not the timing of the required expenditures. A funding requirements analysis allows timing to be considered. The present value analysis allows consideration of both the timing of cash flows and the time value of money.

2.4.1 COST ANALYSIS. A flexible and comprehensive cost work breakdown structure (WBS) was established to ensure that valid cost comparisons could be made in the comparative evaluation process. The cost WBS assures that costs for each manufacturing scenario are organized under the appropriate cost elements and that like costs are compared with another. A summary WBS is shown in Figure 2-11. The basic organization was derived from the categories in the NASA furnished SPS baseline document with allowances made for categories which arise under the lunar and space based scenarios.

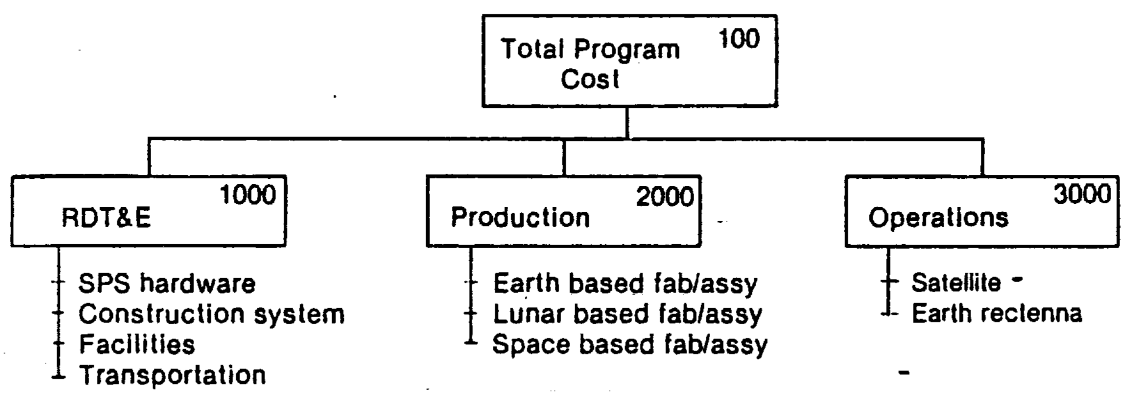


Figure 2-11. SPS summary work breakdown structure.

Costs from the SPS Baseline data were categorized into the WBS format and served as a basis for comparison with the Lunar Resource Utilization (LRU) Concepts. Costs were then developed for each LRU Concept. Each of the three LRU Concepts contain some elements which have never been analyzed or costed before. Other elements are similar to those of previous NASA studies. Due to this similarity, most of the LRU element costs were derived or scaled from those studies. Existing cost estimates for space stations, space construction bases, orbital transfer and launch vehicles were applied to obtain cost relations for propellant depots, habitats, facilities, vehicles and other LRU elements.

Some LRU elements exhibit conceptual and innovative characteristics which are not similar to previously studied space systems. For these elements (e.g., mass driver catapult and manufacturing equipment) costs were based on direct analogies with similar industrial products or services, and cost estimating relationships.

The primary ground rules and assumptions used in making economic estimates are outlined below.

1. Costs are expressed in constant year 1977 dollars. Current prices are assumed. No attempt was made to adjust costs for changes in future supply and demand.

2. Satellites will be produced at a rate of 1 per year for 30 years. Operations Costs are limited to the 30-year period, starting with the operation of one satellite in the first year and ending with the operation of 30 satellites in the 30th year.

3. The following costs are the same for the Earth Baseline and LRU Concepts:
   - SPS Hardware Development (Satellite & Rectenna)
   - Earth Rectenna Production
   - Development/Fabrication of Orbiting Construction Systems

4. No new earth based SPS Hardware Manufacturing Facilities are required for the LRU concepts since only 10 percent of the satellite is constructed of components obtained from earth. The following earth supplied production items were assumed to be purchased from existing earth suppliers:
   - Earth Rectennas
   - Any satellite equipment which cannot be fabricated in space, or is made of material not available from the lunar soil

5. Earth based support facilities such as mission control, administration and sustaining engineering were assumed to be existing and no charges were included for these facilities in either the Earth Baseline or the LRU concepts. The recurring cost of manning and operating these facilities in support of the lunar/space based manufacturing is assumed to be 3% per year of the cost to fabricate the manufacturing facilities. The requirements for lunar and space based launch facilities are assumed minimal and no costs were included for their development or construction.

6. Lunar resources are not used to fabricate the lunar and space based facilities. These facilities are fabricated on earth, then transported to final location and assembled during the facility activation phase.

7. The lunar and space based facilities in all LRU concepts are owned and operated by a single entity that is in business for the purpose of selling power for profit. This entity uses the facilities to manufacture and construct the SPS fleet and

purchases from earth only those materials not available from the lunar soil. The Earth Baseline costs are predicated on the normal way of doing business on earth (i.e., the entity purchases, rather than manufactures, the majority of SPS hardware from independently owned, earth based firms).

Like the Earth Baseline, LRU element costs were categorized into the work breakdown structure in Figure 2-11 and program costs were obtained. A summary cost comparison is shown in Table 2-7. Costs are expressed in $/kW of installed capacity (300 GW). On a nominal basis, total costs of the LRU concepts could potentially provide a significant savings over an earth based approach.

For further comparison, estimated construction costs for terrestrial nuclear and coal fired generating plants are in the 500-1000 $/kW range. From Table 2-6, SPS construction costs (RDT&E + Production) are 1400-1600 $/kW for the three LRU concepts and 2400 $/kW for the Earth Baseline. All of the approaches require a much higher investment in facilities than do current day terrestrial power plants. This is offset however, by lower SPS operating costs. No fuel is required and maintenance is low due to the passive generation system.

Data in Table 2-7 was used to compute the cost of delivering energy to the ground transmission system at the generating system bus-bar. Assuming a 60% capacity factor, the bus-bar generation costs are approximately 7¢/kW-hr for the LRU concepts and 11¢/kW-hr for the Earth Baseline. This estimate includes all carrying charges and operating costs normally included in utility company estimates and assumes each satellite is used for 30 years. For comparison, today's bus-bar cost of a nuclear power plant, in 1977 dollars and at a 60% capacity factor, is about 13¢/kW-hr and the cost of a coal fired power plant is about 12¢/kW-hr (Reference 18).

Table 2-7. Summary SPS program cost comparison.

	Earth Baseline	LRU Concept B	LRU Concept C	LRU Concept D
RDT&E & startup ($/kW)	235.3	405.9	451.6	485.9
SPS hardware	21.0	21.0	21.0	21.0
Construction system	69.0	69.0	69.0	69.0
Facilities & equipment	55.7	229.3	253.0	277.7
Transportation	89.6	86.6	108.6	118.2
Production ($/kW)	2188.3	994.4	1127.2	1048.9
Earth-based fab & assy	2066.7	764.9	848.1	794.7
Lunar-based fab & assy	0	9.8	61.4	84.9
Space-based fab & assy	121.6	219.7	217.7	169.3
Operations ($/kW)	622.2	622.2	622.2	622.2
Total program cost ($/kW)	3045.8	2022.5	2201.0	2157.0

Breakeven curves were constructed to determine the threshold points where the LRU concepts become more cost effective than the Earth Baseline. These are shown in Figure 2-12 in the form of average total cost curves. Without considering the time value of money and cost uncertainties, the threshold was found to lie between 3 and 5 satellite systems. If cost estimates were based on more detailed information the chart would be more significant. Due to the great deal of uncertainty associated with these estimates, the points are likely to vary from the nominals shown in Figure 2-12. This uncertainty is addressed in Section 2.4.3.

The final portion of the cost analysis task was to examine major differences between Earth Baseline and LRU concept costs. Major differences exist in development, transportation and the cost of satellite production. Table 2-8 provides a breakdown of the cost differences between each LRU concept and the Earth Baseline. Since satellite operations costs are the same in both cases, they were omitted from the table. The remaining costs are in the RDT&E and Production Phases. They were allocated between the major categories of transportation and manufacturing. Included is facility, vehicle and RDT&E amortization, vehicle production and maintenance, facility operation and maintenance, startup operations, and propellants. Also included is the cost of purchased parts and material. The LRU concepts are lower in the transportation area by

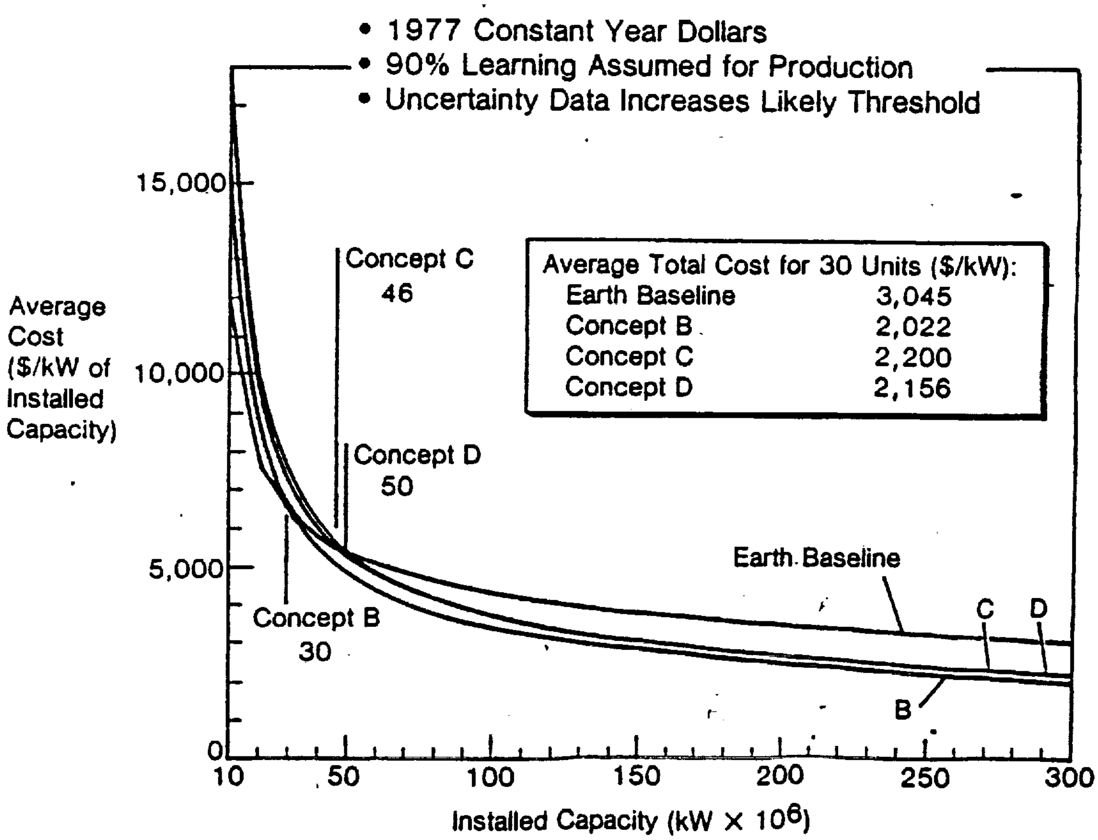


Figure 2-12. Nominal economic threshold of LRU concepts.

$117.8-158.5 billion. This result was expected due to the large reduction in earth launch vehicle payload requirements and the smaller energy requirements to launch the same amount of material from the moon as from earth. Table 2-8 shows the LRU concepts to be lower in manufacturing costs by a similar amount. $18.6 billion of this manufacturing cost is due to a requirement for only one construction system instead of two. Thus, the LRU concept cost to manufacture SPS hardware, up to the point of on-orbit assembly is lower than the Earth Baseline by: $129.8 billion for Concept B, $117 billion for Concept C and $102.8 billion for Concept D. This was a surprising result since it would seem reasonable to assume that space manufacturing would be just as costly as earth manufacturing. The large manufacturing cost differences actually result from a combination of factors. These are discussed next in their order of importance.

Table 2-8. Comparison of costs between the earth baseline and LRU Concept B. total program costs (billions of 1977$)

Category	Cost Difference Between Earth Baseline and LRU Concepts					
	B		C		D	
Transportation		158.5		117.8		145.2
Earth Based	186.4		158.4		173.7	
Lunar Based	− 2.3		− 2.0		− 7.4	
Space Based	−25.6		−38.6		−21.2	
Manufacturing		148.4		135.6		121.4
Earth Based	235.2		235.2		235.2	
Lunar Based	− 8.0		−36.8		−48.2	
Space Based	−78.8		−62.8		−65.6	

1. Earth Manufacturing Chain Influences

The earth based manufacturing chain introduces additional, significant costs which are not present in the LRU scenarios. These are (1) the cost of middlemen and (2) the addition of profit (and the presence of profit pyramiding) by the middlemen, mining companies, processors and manufacturers. This difference is a direct result of groundrule/assumption number (7); that the LRU scenarios assume a vertically integrated manufacturing chain owned by a single entity. The entity makes no profits until power is sold. It requires no profit on the SPS hardware fabricated in space. Only the 10% portion of the SPS which is purchased on earth includes middlemen costs and profits. The Earth Baseline concept on the other hand relies heavily on purchased parts from independent manufacturers. Profit pyramiding in the earth based manufacturing chain, and the presence of the middlemen's labor, overhead and profit, add to the cost of purchased hardware from earth.

2. Manufacturing Facilities

A second factor which contributes to lower LRU concept costs is in the facilities area. The manufacturing facilities and equipment for the LRU options are specifically designed to turn our hardware for a single end product. This results in a smoother, more efficient manufacturing flow than achievable by a group of earth based firms who have diverse interests. LRU concept space facilities are also optimally sized to produce the required output whereas existing earth facilities may (1) have excess capacity that may result in higher overhead charges to buyers or (2) be too labor intensive due to insufficient investment in plant/equipment. Finally, LRU facilities which house manufacturing equipment are less costly than earth based facilities. Although operating environments differ considerably, the earth environment is actually more severe than space due to winds, moisture, snow loads, etc. The more passive environment in space eliminates the need for protective enclosures in many cases, and expended shuttle external tanks can be employed in the fabrication of pressurized facilities. Since the primary use of the external tanks is transportation, the only costs charged to the manufacturing category for their use was in transporting them to the Space Manufacturing Facility location and converting them to facilities.

3. Labor and Overhead

A highly automated manufacturing scenario and extensive use of industrial robots in the manufacturing process results in lower labor costs for LRU concept production, In the LRU options only 1500-1600 personnel were required for the entire mining, processing, manufacturing and assembly process. On earth these processes would require many times that amount of workers for the same output. Not only are costs incurred for the direct labor costs of these workers but they are also incurred in the indirect labor of supporting groups and the overhead associated with them.

The above differences in manufacturing cost are actually a result of a difference in the study assumptions between LRU and the Earth Baseline. The same manufacturing chain and ownership assumptions could have been made for the Earth Baseline scenario, and manufacturing costs similar to those of the LRU concepts would have resulted. Alternatively, the manufacturing chain in space could have been assumed to be like that on earth, with many independent owners. Either assumption was felt to be unrealistic. If such a project were undertaken on Earth, it would be difficult to imagine a single entity owning the entire chain (i.e., the mines, the processing facilities and manufacturing facilities) without getting other enterprises involved. From the standpoint of space based manufacturing with lunar supplied material, this approach would be entirely reasonable; thus the assumption was used in the present study. To determine the effects of this manufacturing assumption on the economic threshold, a sensitivity analysis was performed, the results of which are documented in the next section.

2.4.2 THRESHOLD SENSITIVITY TO MANUFACTURING COSTS. For the purpose of this sensitivity analysis, it was assumed that LRU scenarios included independent firms and middlemen, which resulted in increased manufacturing costs. This increase would occur not only because of profits and additional overhead, but also because of lost efficiencies in the manufacturing process. To test the sensitivity of the economic crossover points to such a scenario it was assumed that the manufacturing costs of LRU concepts are the same as those in the Earth Baseline. From the Cost Analysis results, the total differences in manufacturing between Concepts B, C and D and the Earth Baseline are \$129.8 billion, \$117 billion and \$102.8 billion respectively. If these amounts are added to the LRU concept costs we can determine the effects on the crossover point and uncertainty bands.

The differences in manufacturing costs were allocated to the Lunar and Space Based Manufacturing Costs using ratios of element costs to totals. Costs were further allocated to RDT&E and Production by cost ratios. Economic thresholds were then determined in a similar manner as in the previous analyses. The nominal threshold, in terms of average total cost per kilowatt of installed capacity is provided in Figure 2-13. The figure indicates that, even with the added costs, the LRU concepts are still more cost effective than the Earth Baseline with crossovers at 11.1, 12.0 and 13.4 units.

- 1977 Constant Year Dollars
- 90% Learning Assumed for Production
- Uncertainty Data Increases Likely Threshold

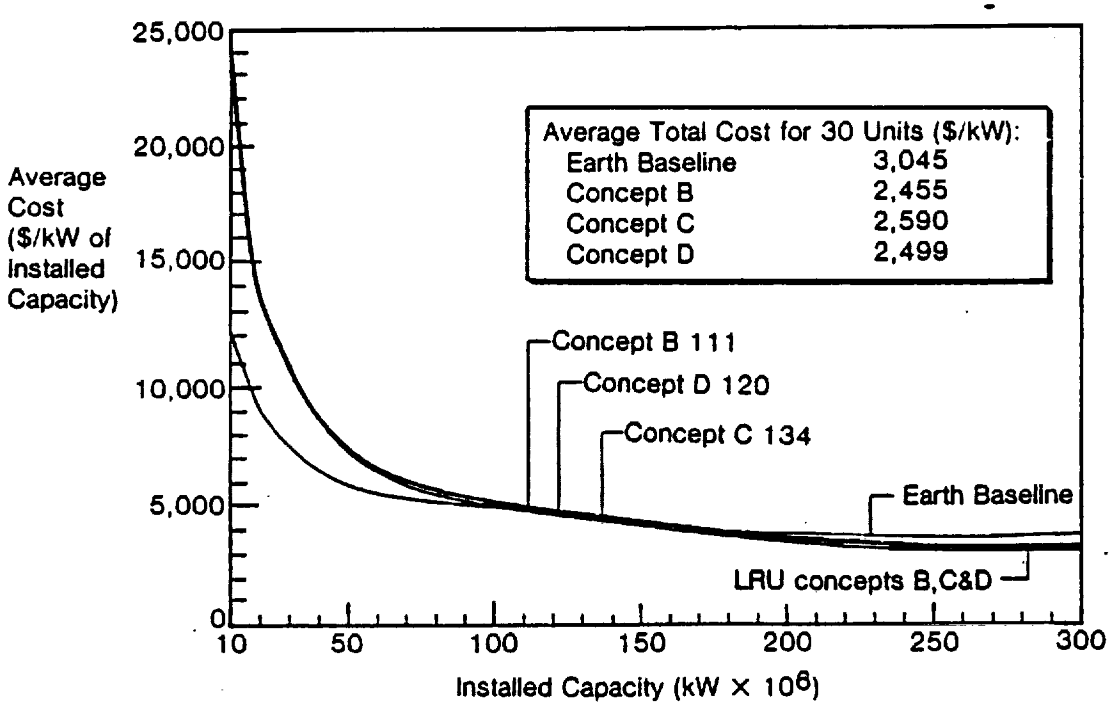


Figure 2-13. Nominal economic threshold for LRU concepts assuming earth baseline and LRU concept manufacturing costs are equal.

2.4.3 COST UNCERTAINTY ANALYSIS.

Cost Uncertainties — The nominal costs previously derived are only point estimates which lie within a range of potential future costs. Our current ability to predict those costs with a great deal of certainty is limited. Uncertainties exist in several areas which can contribute directly to actual program costs being higher or lower than nominal.

The first area is related to supply/demand shifts and their effect on prices. Two factors which contribute to uncertainty in this area are: (1) the dwindling supply of the earth's natural resources which will increase future costs, and (2) the effects of SPS program demand on facilities, material and labor prices. These factors, had they been considered, would have a greater cost impact on the Earth Baseline than the LRU concepts. Such assessments would certainly be appropriate in future studies. In fact, the scarcity of earth's natural resources and increasing costs due to dwindling supply is a major reason for considering lunar resource utilization.

A second major area of uncertainty is the number of unknowns associated with the space/lunar based manufacturing chain. Man's efficiency in and adaptability to space could have major effects on space crew productivity. The amount of earth based support required along with associated facilities have not been defined. Operation and maintenance costs of space based manufacturing equipment are based on earth experience and could vary significantly from the nominal estimates.

Cost uncertainties are also present due to the state of hardware definition and operational characteristics for the optional programs. The scope of the current study was much too limited to define many of the LRU elements with a great deal of detail; this is especially true of enclosure facilities for the space/moon manufacturing equipment, space based launch/recovery facilities and earth based support facilities. It is also true for advanced state of the art systems where details are lacking. The final source of uncertainty is in the development cost of advanced state of the art elements. Problems in technology and hardware development cannot be foreseen and costs could be higher than predicted.

Due to the potential effects of the unknowns on predicted program costs, an uncertainty analysis was performed in an attempt to quantify uncertainties and determine the effect on economic thresholds. The approach to estimating cost uncertainties was one of combining analyst judgment with quantitative techniques. In this study, standard deviation was used as a measure of cost uncertainty and all cost distributions were assumed to be normal for ease of data analysis. It was recognized that cost distributions often tend to be skewed but this should have little effect on the results since, for large numbers of samples (cost elements), the total distribution will approach normality. The objective was to define an interval around the nominal point cost estimates which represent a $\pm 3\sigma$ standard derivation spread from the nominal estimate. This interval theoretically includes 99.7% of the possible variation in costs.

Confidence intervals about the nominal were determined in three distinct steps: (1) cost elements were ranked according to degree of certainty of the estimate, (2) rankings were converted to $\pm 3\sigma$ confidence intervals based on a percent of nominal costs, (3) percentages were applied to nominal costs to obtain dollar value $\pm 3\sigma$ confidence interval for each program phase.

Once the $\pm 3\sigma$ confidence intervals were developed, the effect of uncertainties on economic threshold points was determined. Uncertainty ranges were plotted for each concept in a similar manner as the nominal breakeven curves shown earlier. Figure 2-14 shows the results of the LRU Concept B comparison with the Earth Baseline in terms of average total cost. A 90% learning curve was applied to production costs. The ranges are too broad to ascertain the presence of a crossover. In order to determine the presence of an economic threshold within the 30-unit production phase, the maximum limit of the LRU Concept B range must cross the minimum limit of the Earth Baseline range. This does not occur. The crossover in the Concept B/Earth Baseline comparison could occur at any point in the overlap area of the two ranges,

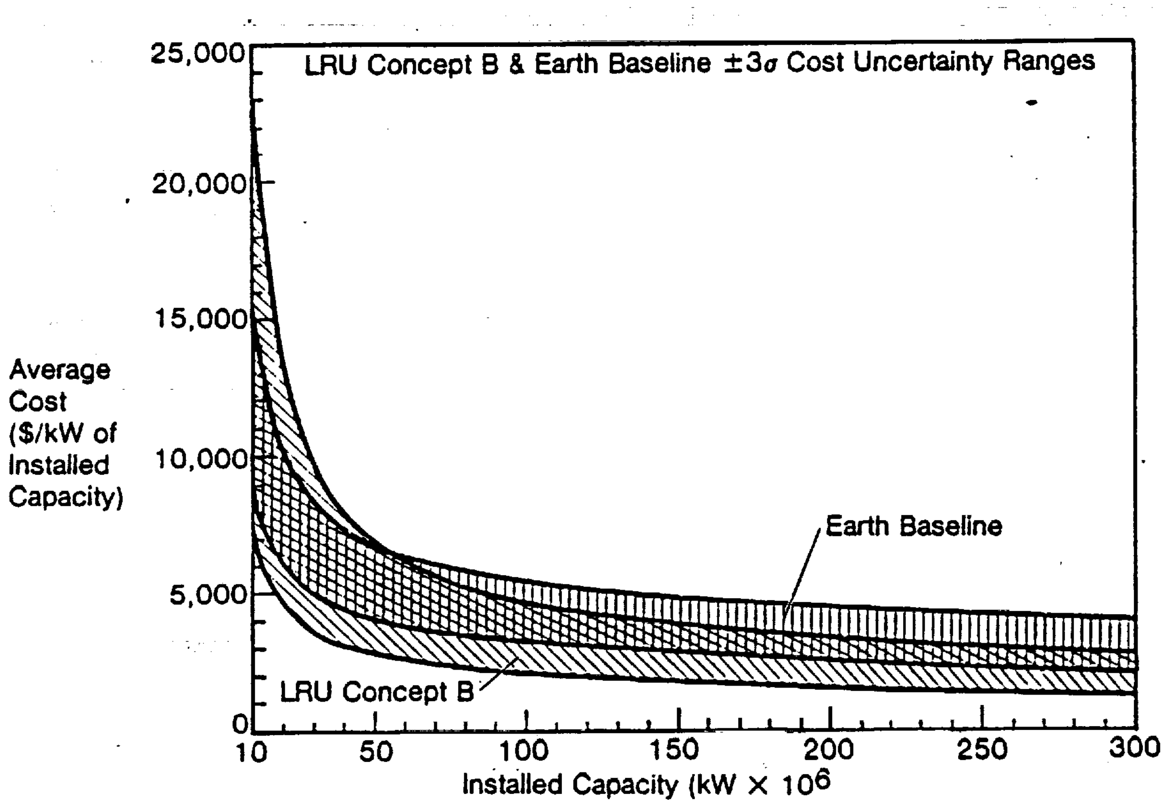


Figure 2-14. Economic threshold for Concept B if cost uncertainties are included.

or at some greater production quantity. Thus, for confidence intervals which include 99.7% of possible outcomes, it cannot be determined which concept is more cost effective. Similar results were obtained for Concepts C and D.

No crossover could be detected within the 30 unit production program considered when using a $\pm 3\sigma$ confidence band, however, as the uncertainty range is narrowed, maximum crossover points can be detected; first at very high production quantities, then at lower and lower quantities as the uncertainty band becomes smaller. Due to the overlap of the earth baseline and LRU option uncertainty bands, the crossover points were of a cumulative nature; that is, they represent the number of units at or below which the LRU options become cost effective. The initial uncertainty bands shown in Figure 2-13 represent ranges of cost within which 99.7% of the actual costs would fall. As these bands are narrowed, it becomes less and less probable that actual future costs would fall within their smaller ranges. The exercise of narrowing down the bands was performed to determine the probability intervals associated with a crossover at 30 production units or less. The value of this exercise is that it allowed a determination of the probability of crossover at or before 30 units for each concept. These probabilities are shown in Table 2-9. Even with the reduced confidence intervals, the probabilities of attaining a crossover within 30 production units is quite high. Concept B shows the highest probability of reaching a crossover with a 92.8% probability. Concepts D and C have probabilities of 88.5% and 86.3% respectively.

The uncertainty analysis was repeated for the case where manufacturing costs for the Baseline and LRU concepts were assumed to be equal. The increased LRU manufacturing costs have a significant effect on the width of the uncertainty range. The added costs more than doubled the original nominal costs for space/lunar facilities and equipment and their operation. This in turn increased the dispersions and resulted in a much wider 3σ confidence band. The conclusions which can be reached are the same as before. With the 99.7% probability interval, the bandwidths are too wide to determine if an economic threshold will be reached within the 30 unit production run. The probability of a crossover at or before 30 units for each concept is shown in Table 2-9. The probability of achieving a crossover is significantly lower than in the original analysis where satellite manufacturing costs are different for the Baseline and LRU Concepts.

Table 2-9. Probabilities of crossover within 30 units of satellite production.

	Probability Percentage	
	Different Manufacturing Costs	Same Manufacturing Costs
Concept B	92.8	64.4
Concept C	86.3	57.0
Concept D	88.5	63.9

The major implication of the uncertainty analyses is that it can be stated with a relatively high level of certainty that an economic threshold will be reached within the 30 unit production run. Even if LRU Concept manufacturing costs are grossly understated, and in fact are more like those of the Earth Baseline, the probability is still fairly high that LRU concepts would be more cost effective than the Earth Baseline. In this case the LRU advantage is due primarily to the savings in transportation alone, rather than in both transportation and manufacturing.

2.4.4 PROGRAM FUNDING SCHEDULE AND PRESENT VALUE ANALYSIS. The performance of a funding schedule and present value analysis assures the efficient allocation of resources. It is a useful tool for use in the selection of alternative investments because it considers not only the magnitude of the program costs but also the timing of expenditures and the time value of money. It also provides insight into the desirability of alternative funding spread options by providing a means to numerically quantify various funding curve shapes. In effect, the present value analysis removes the time variable, so projects are compared on an equivalent basis.

Figure 2-15 shows the results of the program funding schedule analysis. The LRU Concept B spread is superimposed upon the Earth Baseline spread for comparison. Spreads for Concepts C and D were of similar shape and magnitude. In general, the expenditure profiles are indicative of the relative costs of the alternatives. Annual costs were highest for the Earth Baseline, peaking at $25.6 billion in the year 2004 and gradually decreasing to 18.7 billion by the end of the program. When the first SPS becomes operational in the year 2000, cumulative expenditures are approximately

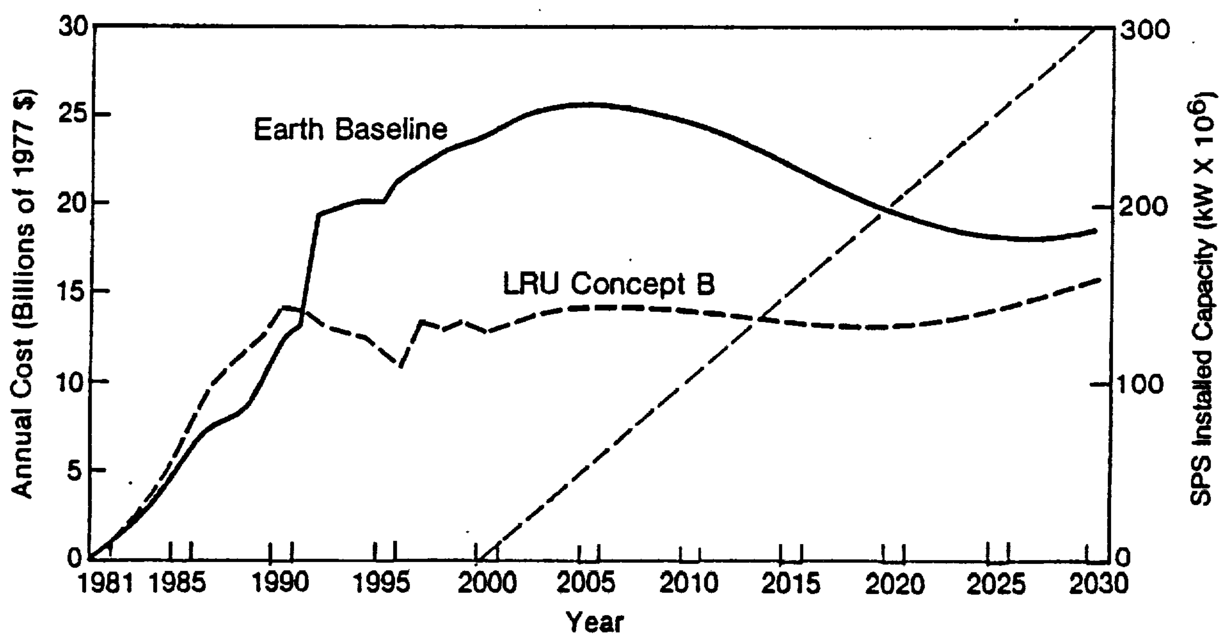


Figure 2-15. Estimated annual expenditures.

31% of total program cost. Annual costs for the LRU options are in the order of $15 billion per year beginning in about 1990. Cumulative expenditures are approximately 34% of the total when the first SPS becomes operational in the year 2000. Based on the lower annual funding requirements for the LRU concepts, they appear to be better alternatives than the Earth Baseline. The annual costs of any one of the programs, in light of the present NASA budget, appear excessive and shed doubts on the capability of a single enterprise to undertake such a program. For a program of this magnitude, a large single entity would probably have to be formed to provide the required funding. To demonstrate the immense size of the SPS program analyzed in terms of energy output as well as dollars, the energy capacity growth is shown in Figure 2-15. The 300 GW maximum reached in the year 2030 compares with a total United States electrical energy capacity of 550 GW in 1977.

The appropriate discount rate for determining present values is in the order of 10 percent. To allow for uncertainty in the discount rate, three rates were actually chosen for the present study: 7%, 10% and 15%. Discounted dollars were determined using each of the three rates and the results are shown in Table 2-10.

Table 2-10. Present Values of the Alternatives.
(billions of 1977 dollars)

Billions of Dollars	Present Value Of Costs Discounted At		
	7%	10%	15%
Earth Baseline	191.7	118.0	61.9
LRU Concept B	139.1	90.9	52.5
LRU Concept C	152.8	100.1	58.0
LRU Concept D	153.7	101.6	59.4

The present values indicate the same relative ranking regardless of discount rate. LRU Concept B has the lowest present value, followed by Concept C, Concept D and then the Earth Baseline. This ranking supports the earlier cost analysis and indicates that, on a nominal basis, all LRU concepts are superior to the Earth Baseline.

2.5 PROGRAMMATICS

Study activities included an assessment of how best to proceed with LRU should a suitably large space production program be authorized. The basic premise was that use of lunar resources should be maintained as a viable construction option through the early phases of program development until sufficient information becomes available to support a decision concerning its suitability and economic effectiveness. In addition, recommended activities to increase understanding of the lunar resource utilization option were identified. These include expanded study work and LRU peculiar technology development activities capitalizing on the results and insights obtained during the performance of this study.

2.5.1 LRU DEVELOPMENT APPROACH. A program to utilize lunar materials for construction of large space systems must proceed through implementation steps which relate to and parallel the development and demonstration of the end product, in this case the SPS. The results of the LRU study indicate that an ambitious space program is required before utilization of lunar resources becomes economically feasible. Prior to embarking on a program of this magnitude, a substantial satellite development effort would be required which is relatively independent of the final location selected for material resources acquisition.

A suitable interaction between an earth baseline construction program and an LRU optional program for construction of similar large space systems has been defined. This was accomplished by assuming that any space program large enough to justify LRU consideration would require an earth-based "proof-of-concept phase" including prototype demonstration, prior to committing to full scale production. During this "proof-of-concept" program activity associated with SPS, parallel efforts can evaluate and demonstrate the effectiveness of lunar resource utilization.

An SPS development and demonstration program will go through at least five major phases prior to the actual production of the operational space system. Figure 2-16 shows the interaction between the SPS demonstration and LRU techbology development parallel programs. Generally, the earth baseline path and LRU path appear to be independent, but in fact offer many opportunities for interaction and cross influence as development progresses.

LARGE SPACE SYSTEM CONCEPTUAL DESIGN PHASE — Baseline activities concentrate on defining the SPS and support elements (launch vehicles, habitats, and construction fixtures) needed to construct the satellite. LRU option work primarily involves assessment of how baseline support elements can be adapted or utilized as-is to conduct the optional program. In addition, conceptional definition of unique LRU elements such as lunar mining, lunar material transport, and space manufacturing is accomplished. Interaction is primarily involved with achieving maximum compatibility with transportation vehicles and infrastructure elements for the two parallel programs.

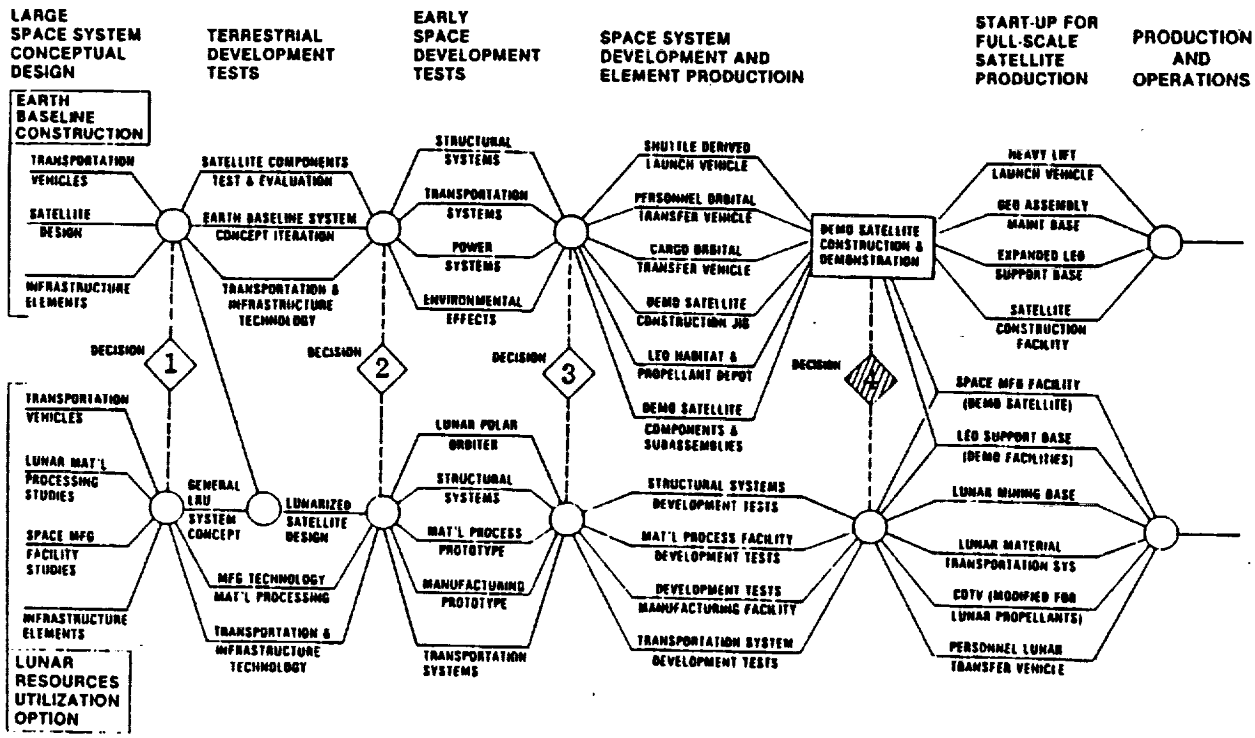


Figure 2-16. Parallel development paths.

TERRESTRIAL DEVELOPMENT TESTING PHASE — These initial development tests are performed on earth to demonstrate technology readiness for both the earth baseline and LRU programs. Interaction is primarily concerned with the effects of construction material origin (earth or moon) on the satellite design.

EARLY SPACE DEVELOPMENT TESTING PHASE — Certain technology demonstrations, especially those at the subsystem level, can best be performed in the system's natural operating environment. These tests will all be launched with Space Shuttle and will provide practical experience with new hardware under realistic operational conditions. Earth baseline program tests are product satellite and transportation system oriented, with special emphasis on the environmental effects of satellite operation and launch vehicle exhaust products. LRU program shuttle launched tests are primarily associated with lunar material processing and manufacturing prototype equipment.

SPACE SYSTEM DEVELOPMENT AND ELEMENT PRODUCTION PHASE — The LRU option development tests comprise a second generation test series to those performed in the preceding phase. The earth baseline construction program, however, develops and constructs those system elements required to build a demonstration satellite. These system elements include transportation vehicles, habitats, and demonstration satellite construction facilities. The demonstration satellite should be of sufficient size to provide useful earth services and will probably require development of a shuttle derived vehicle with increased payload capacity. Interaction between parallel programs includes demonstration satellite construction features and support elements compatible with either commercial program. This phase culminates in operation of the SPS demonstration satellite.

START-UP FOR FULL SCALE SATELLITE PRODUCTION PHASE — Develop and deploy transportation systems and facilities needed to support production and operation of full scale satellites. The parallel paths in Figure 2-16 are interconnected by natural decisions points which require comparative reassessment of progress and continuing viability of the LRU option. A key decision point occurs at demo satellite operation — a choice between the earth baseline and LRU construction options could logically be made at this point. If LRU is selected, a rapid start-up of lunar and space manufacturing facilities will be required to maintain program momentum. As an alternative, lunar resource utilization for satellite construction could be delayed while lunar material compatible satellites are constructed with earth resources. This allows earth-based production and operation of the product while the additional facilities needed for LRU are developed and started up on a more leisurely schedule.

An example LRU SPS program schedule,presented in Figure 2-17, has been generated to span from 1979 through completion of the first commercial satellite. The key milestones used in developing this schedule were obtained from the "SPS Concept Development and Evaluation Program" reference system report, issued by DOE and NASA in October 1978. The key milestones are:

- Joint DOE-NASA Final Program Recommendations - June 1980
- Technology Availability Date is 1990
- SPS Operational Date is 2000

In addition, we have assumed that a demonstration satellite will be built and tested three years following the technology readiness date. We think a scale demonstration of useful space power generation and transmission will be a political requisite to embarking on a commercial SPS program. Two additional key milestones have been included with those used for schedule development. The achievement of interim technology goals in mid-1985 leads to the decision to build a demonstration satellite. This decision promotes escalated technology development testing in space, and provides go-ahead for launch vehicle final design and production. The other milestone is commitment for a commercial SPS program. This is coincident with successful testing of the SPS demonstration satellite in early 1993. The year 2000 was a given earth baseline SPS operational date, and is also shown as the date for the first commercial LRU SPS on-line. Our original approach assumed that one or more additional years might be needed between successful

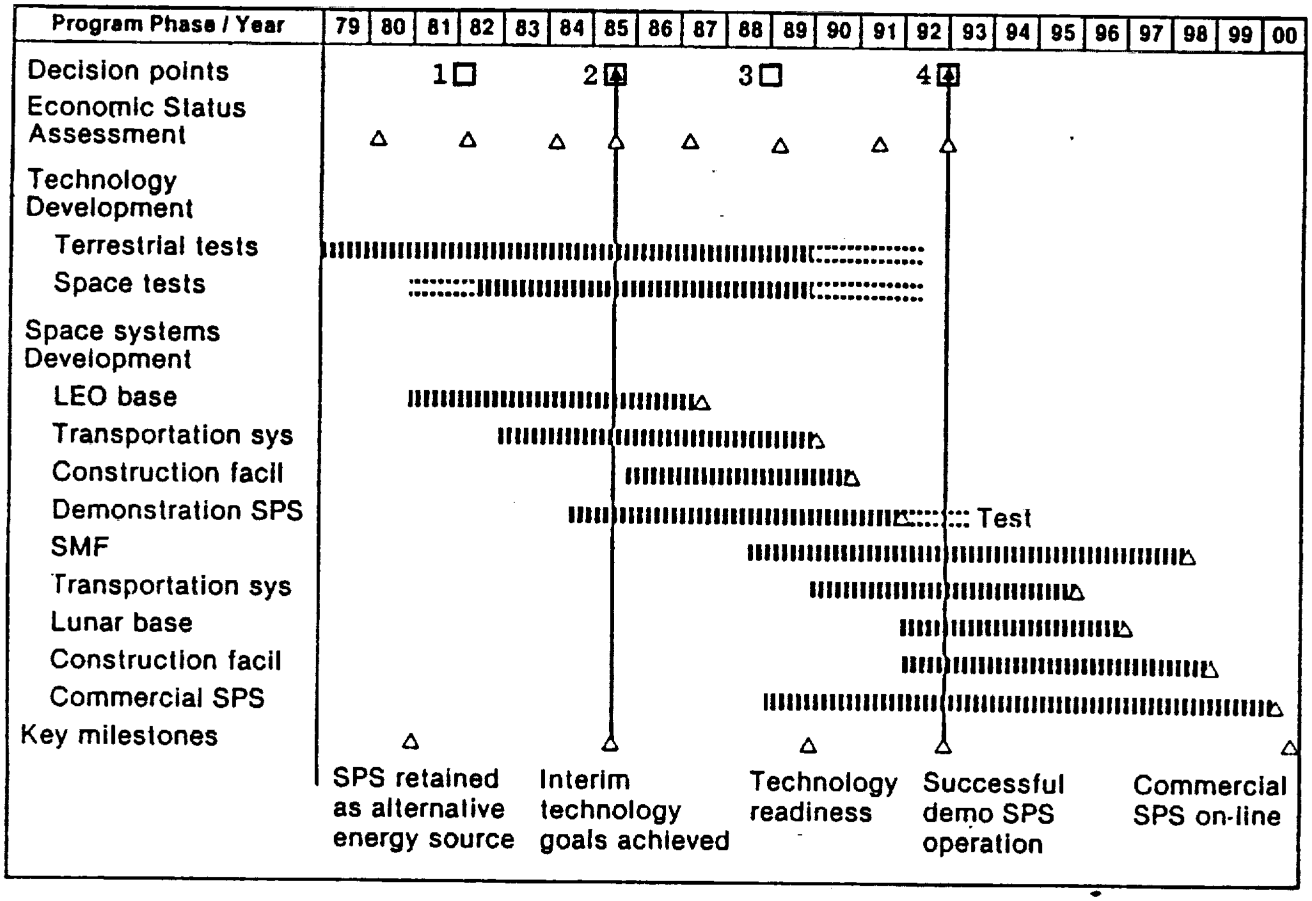


Figure 2-17. Example LRU SPS development schedule.

demonstration satellite operation and commercial SPS on-line to develop the LRU peculiar system elements and perform the more complicated start-up operations. We discovered, however, that the development of LRU peculiar elements and common elements could be conducted in parallel and the required three-year LRU start-up could be scheduled within the 1993-1999 span to support the mid-2000 date for completion of SPS construction.

The two major program decision points identified in Figure 2-17 occur in mid-1985 and early 1993, and correspond to the commitment to construct a demonstration satellite and initiation of a commercial SPS program, respectively. Specific accomplishments must be achieved by these dates to support each decision. These accomplishments are listed in Table 2-11. The mid-1985 decision point accomplishments consist of launch vehicle and SPS technology developments needed to construct the demonstration satellite. These accomplishments are relatively independent of LRU considerations, and therefore the items listed in the left column are equally applicable to either the earth baseline or LRU SPS program. It is especially important for the LRU program, however, that these demonstration satellite development requirements do not preclude or adversely influence the eventual use of lunar resources for SPS construction. The early 1993 accomplishments listed in the right column are primarily associated with lunar resource utilization.

Table 2-11. Critical development criteria.

To support a decision to construct a demonstration SPS Target decision date — mid 1985	To support a decision to initiate a commercial LRU SPS program Target decision date — mid 1993
Commit to develop • LEO space platform • Shuttle-derived vehicle • Personnel orbital transfer vehicle **Demonstrate technology readiness** • Ion-electric COTV • Propellant depot • Large space structures • SPS microwave power transmission • Low-cost solar cells **Assurance of** • SPS economic competitiveness • SPS environmental issues resolution	**Successful demonstration of** • Solar power demonstration satellite • In-space processing of simulated lunar material • Silicon refining • Oxygen liquefaction • Space manufacturing • Modular habitats **Demonstrate technology readiness** • Mass driver catapult • Mass catcher • Ion-electric COTV oxygen thrusters **Completion of lunar resources survey** **Economic substantiation of LRU SPS**

The achievements identified in Table 2-11 are associated with the development status of required technologies and commitments to produce critical system hardware elements. In conjunction with these achievements, incremental assessments of lunar-resource utilization economic feasibility must be performed. LRU cost effectiveness status should be updated at regular intervals to provide visibility into the effects that technology achievements have on the overall viability of satellite construction using lunar resources.

2.5.2 RECOMMENDED SUBSEQUENT STUDY TASKS. A total of thirty individual LRU related study activities were identified to expand the work conducted during performance of contract NAS9-15560. These activities are oriented toward reducing the uncertainties contained in the technical and economic data used for LRU assessment. The thirty tasks were organized into five categories, or recommended study packages.

- UPDATED STUDY TASKS — Results of the LRU study and reviewer comments have suggested modifications to some of the work performed. These revisions include: 1) personnel launch with SDV rather than Space Shuttle, 2) improved transfer performance for COTV's due to reduced attitude control requirements, 3) incorporation of these and other later study findings into an updated evaluation of steady state operations, and 4) revised economic analysis incorporating these results.

- EXPANDED TRADE STUDIES AND ANALYSES — Incorporates investigations beyond the current LRU study scope including trade studies of: 1) mass catcher configuration, 2) lunar material processing, 3) processing location, 4) lunar base location and power supply, 5) SMF location, and 6) alternative start-up techniques including bootstrapping.

- LRU ELEMENT CONCEPTUAL DEFINITION — Expanded definition of important LRU transportation system elements including: 1) cargo orbital transfer vehicle, 2) personnel orbital transfer vehicle, 3) lunar transfer vehicle, 4) shuttle derived vehicle, 5) mass driver catapult, and 6) mass catcher.

- MATERIAL PROCESSING AND SPS TRADE STUDIES — Includes more detailed assessment of options for: 1) oxygen production, 2) silicon refining, 3) SPS production, 4) SPS redesign to maximize lunar resources utilization, and 5) possible effects on SPS configuration and material requirements due to technological breakthroughs.

- NEW STUDY TASKS — Encompass a broad range of expanded activities including: 1) extraction of minor lunar materials, 2) SMF conceptual design, 3) modular habitat design, 4) utilization of asteroidal resources, 5) SMF sensitivity to the level of automation, and 6) bootstrapped production analysis.

2.5.3 RECOMMENDED TECHNOLOGY DEVELOPMENT TASKS. Thirteen technology development tasks have been identified as initial steps toward the eventual attainment of LRU capability. These tasks all consist of laboratory experiments to demonstrate processes and/or first generation prototype hardware.

- Development of Ion-Electric Thrusters using Oxygen Propellant
- Development of In-Space Oxygen Liquefiers
- Research on Mass Driver Catapult Linear Electromagnetic Accelerator
- Research on Mass Catcher Material Stream Arresting Equipment
- Research on Large Space (and Lunar Surface) Radiators
- Research on Robotics Suitable for General Purpose Space Industrialization
- Production of Solar Cells by Molecular Beam Epitaxy (MBE)
- Research on Electrolysis of Silicates
- Production of Foam Glass from Lunar Type Silicates
- Vacuum Distillation and Dissociation of Lunar Type Silicates
- Production of Fiberglass Filaments from Lunar Type Silicates
- Vapor Phase Deposition of Thick Sheet and Plate of Iron and Aluminum Alloys
- Vapor Deposition of Thin Silica Glass for Solar Cell Substrates and Covers

All these early conceptual evaluations of space processes or space system performance would be conducted in vacuum chambers. Short duration low g testing could be accomplished via drop tower or on-board a KC-135 aircraft. Eventually, however, many preferred

LRU processing and manufacturing techniques will require demonstration in their expected operating environment. These tests would be accomplished via the space shuttle, either as special dedicated experiments or in conjunction with Spacelab or a science applications platform. The LRU related technology areas which at this time appear to require verification with space experiments are listed in Table 2-12.

Table 2-12. LRU shuttle technology experiments.

- Vapor deposition of aluminum & iron on a molybdenum strip
  - Perform vacuum deposition in zero-g
  - Demonstrate metal separation from Mo sheet following deposition
- Melting & casting of aluminum, iron & sendust (85% Fe - 10% Si - 5% Al)
  - Perform casting at zero-g & low controlled g
  - Demonstrate both permanent metal mold & sand-plaster mold casting
- Reacting SiO_2 to form high-purity silica glass
  - Manufacture of thin silica sheet & glass filaments
- Manufacturing of foamed glass elements from simulated native lunar glass, including structural shapes & waveguide sections
- Electroplating aluminum with copper in zero-g
- Vapor depositions of aluminum on silicon wafers through maskant
- Liquefaction of oxygen in zero-g & 1/6 g

3

CONCLUSIONS & RECOMMENDATIONS

3.1 CONCLUSIONS

- SOLAR POWER SATELLITE, OR SOME EQUIVALENTLY MASSIVE PRODUCT, IS REQUIRED TO SUPPORT LUNAR RESOURCES UTILIZATION (LRU) CONSIDERATION — The comparative assessment of satellite construction performed with earth materials versus lunar materials conducted by this study indicated that at least several hundred thousand metric tons of product are required to support LRU consideration. Therefore, a massive satellite of which a significant quantity is produced is required to initially justify the LRU option.

- EARTH MATERIAL REQUIREMENTS ARE A GOOD INDEX FOR INITIAL EVALUATION OF LRU CONCEPTS — Earth material requirements (EMR) analyses were proposed and used early in the study to evaluate options within basic LRU approaches, and to develop specific system concepts. Based on the study's economic analysis results, we are convinced that EMR is a useful comparative analysis tool. EMR comparison aids understanding of specific LRU implementation options without the attendant complexities of an economic analysis. EMR correlates well with the subsequently determined economic viability of the three LRU concepts.

- LRU OFFERS A POTENTIAL 90% REDUCTION IN EARTH PAYLOAD REQUIREMENTS — The substitution of lunar materials for 90% of the reference solar power satellite mass resulted in a corresponding 90% reduction in the earth payload mass plus an equivalent decrease in launch vehicle propellants and resulting atmospheric pollution. These lower payload requirements also permit use of a smaller earth launch vehicle, such as a Shuttle derived vehicle. Increased substitution of lunar resources should be possible in an LRU compatible satellite design, which will further reduce earth payload requirements.

- LRU OFFERS THE ADDED BENEFIT OF REDUCED EARTH ENERGY CONSUMPTION — Utilization of lunar resources for propellants and construction materials requires use of extraterrestrial energy sources (solar energy) for their processing and manufacturing. This, plus the large reduction in earth manufactured satellite components and earth launch vehicle flights, results in reduced consumption of terrestrial energy and resources to support an equivalent satellite program.

- ALL THREE LRU OPTIONS PROVIDED SIMILAR BENEFITS COMPARED TO THE EARTH BASELINE, WITH THE CONCEPT WHICH CATAPULTED LUNAR MATERIAL BEING BEST — The earth material requirements analysis and subsequent economic analysis indicated that each of the three LRU options was potentially superior to the reference earth baseline. Furthermore, the material mass requirements and costs for the LRU options were relatively close together, although the concept which employed an electromagnetic catapult for delivering lunar material into space was clearly the best of the three.

- ALTERNATIVE LUNAR MATERIAL PROCESSING TECHNIQUES APPEAR FEASIBLE — Several lunar material processing concepts were evaluated for their ability to recover silicon, metals, and oxygen from lunar soil. Each of these concepts offered some promise of fulfilling the processing requirements and no clear-cut first choice was obvious. Thus, lunar resources utilization is in the enviable position of having several acceptable processing methods to assess further. These options should be addressed by early technology studies.

- SILICON SOLAR CELL PRODUCTION FACILITIES COMPRISE THE MOST MASSIVE EQUIPMENT REQUIREMENT & ARE THE SECOND HIGHEST POWER CONSUMER — Solar cell production facility requirements were found to dominate other facility needs associated with solar power satellite manufacturing. Based on the sensitivity of all LRU system concepts to this single facility requirement, further material processing evaluation activities should be concentrated in this area. Solar cells manufactured of materials not available on the moon (Gallium Arsinide) are not a viable option for an LRU solar power satellite.

- LRU ECONOMIC BENEFITS ACCRUE FROM LOWER TRANSPORTATION COSTS — Transportation benefits are due to an order of magnitude reduction in earth launch vehicle payload requirements. This reduction more than compensates for the added LRU space transportation vehicles such as cargo orbital transfer vehicles and the mass driver catapult.

- LRU ECONOMIC BENEFITS MAY ALSO BE REALIZED BY UTILIZING AN EFFICIENT SPACE MANUFACTURING APPROACH — If a vertically integrated manufacturing chain, owned and operated by a single entity, is assumed for the LRU program, then further program cost reductions can be achieved. A vertically integrated facility sequentially performs all necessary processing and manufacturing operations and is specifically configured to produce the required end product at a specified rate. This approach offers substantial savings over earth baseline production which assumes use of many existing non-optimum independent facilities and intermediate handling, shipping, and warehousing activities.

- CURRENT LRU COST ESTIMATES ARE HIGHLY UNCERTAIN, HOWEVER, STUDY RESULTS INDICATE A REASONABLE PROBABILITY THAT LUNAR RESOURCES UTILIZATION WILL BE COST EFFECTIVE WITHIN 30 SOLAR POWER SATELLITES — Economic analysis of LRU and reference earth baseline construction programs resulted in estimated costs having a high degree of uncertainty. However, the study results did indicate a 57 to 65% probability that LRU concepts could be cost-effective due to transportation benefits alone, within the assumed production of 30 10 GW solar power satellites at a rate of one per year. When LRU benefits from both transportation and efficient space manufacturing facilities are included, the probability of LRU concepts being more cost effective than the earth baseline is quite high, and ranges from 89 to 93%.

- LUNAR RESOURCES UTILIZATION SHOULD BE MORE ATTRACTIVE FOR CONSTRUCTION PROGRAMS LARGER THAN 30 SOLAR POWER SATELLITES — If a solar power satellite program is implemented, it is likely that considerably more than 30 units will be constructed. The potential benefits associated with LRU; reduced earth material requirements, atmospheric pollution, terrestrial energy consumption, and program cost, should be even more attractive for a larger space construction program.

3.2 RECOMMENDATIONS

- SINCE LUNAR RESOURCES UTILIZATION (LRU) OFFERS POTENTIAL BENEFITS, IT SHOULD BE RETAINED AS AN OPTION FOR PROGRAMS OF SUFFICIENT SCALE — Even though many technical and economic uncertainties are associated with LRU, the concept offers substantial advantages, and deserves to be studied further.

- PERFORM IN-SPACE PRODUCTION OPERATIONS USING A VERTICALLY INTEGRATED MANUFACTURING PROCESS, OWNED AND OPERATED BY A SINGLE ENTITY — Study economic analysis results indicated that an integrated manufacturing approach was significantly more cost effective than multiple independent facilities for construction of solar power satellites utilizing lunar resources. The integrated approach is realistic for initiation of an LRU program, although an appropriate legal framework must be implemented.

- ACCOMPLISH LRU TECHNOLOGY DEVELOPMENT IN PARALLEL WITH DEVELOPMENT OF AN EARTH BASED SATELLITE PROGRAM — Solar power satellite (SPS) programatic evaluation indicates the need to establish proof-of-concept with earth materials prior to embarking on a commercial SPS production program utilizing either earth or lunar resources. The schedule for SPS development through proof-of-concept to completion of the first commercial satellite is unaffected by resource origin if parallel development efforts are conducted for LRU technology and the SPS satellite programs.

- INITIATE EXPERIMENTAL INVESTIGATION OF LUNAR MATERIAL PROCESSING — Practical laboratory experience with various processing techniques for recovering useful elements from simulated lunar material is an urgently needed next step in LRU evaluation. This activity could yield substantial results with very modest funding commitments.

- CONTINUE SUPPORT OF MASS DRIVER TECHNOLOGY DEVELOPMENT — Of the various LRU techniques studied, Concept B employing the mass driver catapult for delivery of lunar material into space offered advantages of lowest earth material requirements and lowest program cost. The catapult also accomplishes lunar material launch without release of exhaust products into the lunar environment. Early development work at Princeton and MIT has been very encouraging and NASA support of this work should continue.

- INITIATE EXPERIMENTAL EVALUATION OF OXYGEN AS PROPELLANT FOR ION BOMBARDMENT THRUSTERS — One of the potential earth payload reductions effected by LRU is propellant for orbital transfer vehicles. If oxygen can be successfully used in ion bombardment thrusters, as postulated by this study, then substantially reduced earth payload requirements result. Technology development activity should be initiated to evaluate the feasibility of this propulsion technique.

4

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